STRATH TERRACE AND KNICKPOINT FORMATION IN A COASTAL BASIN DRAINING TO THE CASCADIA SUBDUCTION MARGIN, SMITH RIVER, NORTHERN CALIFORNIA

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ABSTRACT

Strath terrace and knickpoint formation along mainstem channels are indicators of landscape response to tectonic and climatic forcing in the Smith River watershed in northwestern California. Knickpoints in the Smith River basin are manifest as a distinct point where there is a break in slope of the longitudinal profile at the upstream end of an oversteepened reach, the knickzone. Two types of knickpoints occur. At larger drainage areas in the lower portion of the basin, knickpoints and associated downstream knickzones occur within rock types with no significant difference in rock strength as confirmed by Schmidt hammer measurements. There is a distinct upstream convergence of the modern channel with the lowest elevated strath surface along these knickzones, resulting in elevated strath surfaces downstream of the knickzones. We infer that the knickpoints are migratory and that the straths are more vertically separated from the modern channel only after the knickpoint has migrated upstream. Reconstructed paleo-longitudinal profiles project to oxygen isotope stage 5e marine terraces near the coast and suggest that base-level fall as a result of falling sea level following late Pleistocene eustatic sea level highstands may engender migratory knickpoints now preserved upstream. At smaller drainage areas in the upper portion of the basin, the only knickpoints present in channels are those associated with large landslides that mobilize entire hillslopes into the channel and thereby force a channel response.

Extensive preservation of strath terraces throughout the basin indicates that strath terraces record base-level lowering and subsequent incision of the river. In lower portions of the basin incision is achieved by knickpoint migration, producing strath terraces with long profiles that are nonparallel to the modern river profile. In upper portions of the basin periods of vertical incision and lateral planation are related to climate-driven fluctuations in sediment production on channel hillslopes resulting in strath terrace long profiles that do parallel the modern river profile.
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INTRODUCTION

The northwestern-most corner of California lies along the uplifting margin of the Cascadia forearc basin. External factors controlling drainage basin evolution are eustatic base-level changes, differing rates of tectonic uplift, and climate related fluxes in sediment supply and discharge.

The 1,877 km² Smith River watershed is in a dynamic geomorphic and tectonic setting in that the mainstem river empties directly into the Pacific Ocean on the west; and, 46 km to the east on the 1,954 m elevation headwater divide, the basin has hosted multiple alpine glaciers during the oxygen isotope stage (OIS) 2 (18 ky) glacial period (Shackleton and Opdyke, 1973). Furthermore, the basin is on the upper plate of the Cascadia subduction zone with the deformation front of the overriding North American plate only 85 km to the west offshore of the river mouth. The basin sits on top of the subduction zone megathrust, which ranges in depth below the watershed surface from 16 km at the mouth on the western edge of the basin to 27 km at the drainage divide on the eastern edge of the basin (McCrary et al., 2006; Burgette et al., 2009). The direct discharge to the ocean means the watershed is subject to base-level changes caused by eustatic sea level fluctuations tied to climate change. In contrast, climatic fluctuations in the headwaters produce glacial and periglacial alpine conditions that alternate with warmer intervals, resulting in variability in sediment supply and discharge.

For a coastal basin that drains to the ocean, eustasy ultimately controls base-level. A base-level fall at the mouth of a drainage can initiate an upstream propagating wave of
incision in the form of a migrating knickpoint (Gardner, 1983; Seidl and Dietrich, 1992; Crosby et al., 2005; Wobus et al., 2006; Crosby and Whipple, 2006; Hayakawa and Oguchi, 2009). On a longitudinal profile, a knickzone is a reach of relatively high gradient located between lower gradient reaches, and the knickpoint is the distinct inflection point separating a knickzone from a lower gradient reach upstream (Seidl and Dietrich, 1992; Wobus et al., 2006; Crosby and Whipple, 2006; Hayakawa and Oguchi, 2009). Migratory knickpoints may also be initiated by faulting across a stream profile. In contrast, stationary knickpoints can be formed from mass-wasting events (e.g. Phillips et al., 2010) or by variations in rock strength among lithologic units that the river flows through (Wohl, E. E., 1993; Wohl, E. E., 2002; Snyder et al., 2003).

Using digital elevation model (DEM) analysis supported with field surveys, this study investigates the role that climate, tectonics, and lithology have played in knickpoint and strath terrace formation in the Smith River basin, a bedrock dominated watershed draining to the Cascadia subduction margin in northwestern California (Figure 1). Recent research has focused on the applicability of characterizing landscape evolution using DEM’s and stream profile analyses of bedrock river systems (Snyder et al., 2000; Kirby and Whipple, 2001; Snyder et al., 2003; Wobus et al., 2006; Anderson, 2008). By using and modifying the empirical and theoretical relations determined by Hack (1957; 1973) and Leopold et al. (1964), a power-law function that has been observed empirically across many geologic settings can be utilized where stream gradient is described by:

\[ S = k_s A^\theta. \]  

\( \text{(1)} \)
Linear regression on a log-log plot of the slope ($S$) and drainage area ($A$) can produce the steepness index ($k_s$) and concavity index ($\theta$) where $\theta$ equals the regression slope and $k_s$ equals the y-intercept. Steepness index is a more generalized version of the stream-gradient index developed by Hack (1973).

A derivation of equation 1 can be written as:

$$S = \left(\frac{U}{K}\right)^{1/n}A^{-m/n}$$  \hspace{1cm} (2)

where $U$ is uplift and $K$ is the erosion coefficient. Exponents $m$ and $n$ can be determined directly from the linear regression of channel slope versus drainage area on a log-log plot. Comparing equations 1 and 2, it is evident that steepness index ($k_s$) and uplift ($U$) are directly correlated. It has been shown that uplift rates vary independently of $\theta$ (Snyder et al., 2000). Using a constant concavity index ($\theta_{ref}$), values of $k_{sn}$ (normalized steepness index) can be compared directly to make inferences about uplift (Snyder et al., 2000; Snyder et al., 2003; Wobus et al., 2006; Whipple et al., 2007).

A stream at equilibrium will reach a steady state that can be defined by a single $\theta$ and $k_s$ (Snyder et al., 2000). An equilibrium stream will form an ideal longitudinal profile that is preserved over time if climate, discharge, sediment supply, and uplift remain constant (Mackin, 1948). Deviations from this ideal state (e.g. knickpoints) may appear to contradict the empirical results from equation 1, but it is these aberrations that
can be used to decipher information related to lithologic, tectonic, or eustatic driving mechanisms (Wobus et al., 2006).

The specific objectives of this research were to (1) determine relative amounts of tectonic uplift rate among the three major sub-basins in the Smith River watershed through the analysis of stream profiles; (2) determine what role do lithology, hillslope processes, tectonics, and climate (in the form of eustatic base-level fluctuations) have on the formation and distribution of knickpoints within the basin; and (3) evaluate the drivers of incision and lateral planation resulting in strath terrace formation and distribution by mapping and surveying remnant terrace surfaces along the Middle Fork, South Fork, and mainstem Smith River.

FIELD AREA

The Smith River is a high relief, bedrock-dominated river situated in the northwestern-most corner of California, and southwestern Oregon (Figure 1). The three major forks (the North, Middle, and South) and the many tributary creeks collectively form a dendritic drainage pattern (Figure 2). The river’s elevation ranges from 1,954 m at Bear Mountain, in the headwaters of the South Fork, to sea level at the river’s mouth near the California-Oregon border. The watershed drains an area of 1,877 km² and extends 46 km inland at its eastern edge along the crest of the Siskiyou Mountains. Stream channel morphologies range from colluvial in headwater reaches, to bedrock, boulder cascade, and step-pool in upper-basin locations, to bedrock and riffle-pool in mid-basin locations, and finally to meandering pool-riffle and plane-bed alluvial in the
lower basin. The town of Crescent City lies just outside the watershed along its western edge. Located approximately 150 km north of the Mendocino triple junction and 85 km east of the deformation front of the Cascadia margin (Figure 1), the Smith River basin lies above the transitional zone of strain accumulation on the plate interface (Burgette et al., 2009).

The basin geology is dominated by the western Jurassic belt and western Paleozoic and Triassic belt of the Klamath Mountains geologic province (Figure 3). These terranes, which were intruded by intermediate to ultramafic plutons primarily in the Mesozoic, are interpreted as a structural sequence of east dipping thrust sheets, younging east to west, formed by accretion of different oceanic and island-arc assemblages (Irwin, 1964; Irwin, 1981; Saleeby et al., 1982; Harper, 1984). The Josephine ophiolite and overlying Galice Formation are part of the western Jurassic belt and underlie the majority of the field area. The Josephine ophiolite is a complete ophiolite consisting of peridotite (partially to completely serpentinized), gabbro, a diabase dike complex, and metavolcanics (pillow lava, greenstone, and breccia). The ophiolite is conformably overlain by the Galice Formation, which consists of marine slate with a minor metagreywacke and metavolcanic component (Harper, 1984). The Klamath belts are bounded on the west by the Coast Range fault (‘South Fork fault’ of Irwin et al., 1974), along which greywacke and mélange units of the Eastern belt of the late Mesozoic aged Franciscan Complex are thrust below the Klamath rocks (Aalto, 1989). Overlying the Franciscan Complex along the Crescent City coastal plain is the Pliocene-Pleistocene fossiliferous marine siltstone and sandstone Saint George Formation (Diller, 1902;
Maxson, 1933; Stone, 1993; Aalto et al., 1995). Maxson (1931) defined the marine and terrigenous poorly consolidated sands interbedded with clay, which overlie the Franciscan Complex and Saint George Formation as the Battery Formation. The Battery Formation, which is a marine terrace deposit (Polenz and Kelsey, 1999), is interpreted to be late Pleistocene in age based on fossils, soil correlation, and amino acid racemization age correlation of the clam *Saxidomus giganteus* (Addicott, 1963; Kennedy et al., 1982).

The basin is one of the wettest locations in California with annual average precipitation ranging from 170 cm in Crescent City to 250 cm in Gasquet (Figure 2) (NOAA, 2000). Precipitation occurs primarily as rainfall although snow is common in winter in the upper watershed. Annual mean discharge on the Smith River is 106 m$^3$/s as measured in Hiouchi, along the mainstem (Figure 2). Discharge routinely reaches 500-1,500 m$^3$/s during winter storm events and reached 6,456 m$^3$/s during the 1964 flood, the highest on record (USGS Water-Data Report, 2010). Because of high precipitation amounts, steep hillslopes, poorly developed serpentine soils with low infiltration capacity, and the lack of any dam or flow diversion in the basin, runoff response time is short during rainfall events.

This research focused primarily on the South Fork, Middle Fork, and mainstem Smith River (Figure 2). On the mainstem, Middle Fork and South Fork, road access to locations is relatively good, while it is nearly non-existent on the North Fork. Therefore, the North Fork was omitted from most aspects of the research except for the stream profile analysis.
RESEARCH APPROACH

Geographic Data Sources

Geomorphic analysis in the Smith River watershed employed multiple data sets incorporated into the Geographic Information System (GIS) software ArcMap 9.3.1. These data sets (detailed in Appendix A) include a USGS 10 m digital elevation model (DEM) available for the entire watershed, a high-quality 1 m Light Detecting and Ranging (LiDAR) derived DEM available for only a select portion of the watershed, and 1 m National Agriculture Imagery Program (NAIP) satellite imagery (from 2009) of the entire watershed. Additionally, 1:16,000 U.S. Forest Service color aerial photographs taken in 1975 were available for the entire watershed.

Strath Terrace Mapping and Surveying

Stream terraces were identified using the aerial photographs and then digitized onto the NAIP imagery in ArcMap. In some locations, differences in vegetative cover between 1975 and 2009 made it difficult to accurately digitize terraces on 2009 satellite imagery that were identified on 1975 aerial photographs. In these cases, terraces were directly mapped on the aerial photographs and then scanned and georeferenced within ArcMap. Terraces were then digitized from the georeferenced aerial photographs and overlain on the NAIP imagery. In select cases in the lower watershed, the local availability of LiDAR data allowed terraces to be directly mapped on a hillshade model created in ArcMap from the 1 m LiDAR-derived DEM.
With the exception of the few cases where LiDAR could be used, mapped terraces had poor elevation resolution because they were mapped onto the 10 m DEM base.

Terrace elevations needed to be of higher vertical resolution in order to compare terrace elevations to stream profile elevations. Terrace elevations and adjacent channel water surface elevations were surveyed using real-time kinematic (hereinafter referred to as RTK) satellite positioning technology. We used TOPCON GR-3 receivers, which achieve precisions that are typically 3.0 cm horizontal/5.0 cm vertical or better. Appendix B describes the details of the TOPCON RTK deployment.

**Stream Profile Analysis**

Stream longitudinal profiles were constructed using the 10 m DEM. A GIS toolbar and MATLAB codes were acquired from http://www.geomorphertools.org, an open-source package that can compute detailed single-channel profile data and multichannel batch data. DEM and flow accumulation raster files for each fork and for select major tributaries were exported and analyzed in MATLAB. Data smoothing was performed using a 250 m smoothing window. Data smoothing helps to eliminate profile “stair-step” features, which are characteristic of profiles produced from 10 m DEM’s (Whipple et al., 2007). Whipple et al. (2007) provide a detailed description of the DEM preparation and MATLAB analysis.

Slope-area plots were constructed for each fork and tributary analyzed. The plots were reviewed to determine $A_{cr}$. $A_{cr}$ is a critical drainage area at which the stream transitions from colluvial-process dominated to fluvial-process dominated (Tarboton et
al., 1989; Montgomery and Foufoula-Georgiou, 1993; Wobus et al., 2006; Whipple et al., 2007). This transition was easily recognized on the slope-area plots as a sudden decrease in slope of the data. By averaging values from all streams analyzed, an $A_{cr}$ value of $10^6$ m$^2$ was determined for the study area.

A 500 m moving window was chosen as the sampling interval for each stream profile. Data points from the colluvial process dominated length of the stream (i.e. upstream from $A_{cr}$) were not used in the regression of slope-area data because they are not described by equation 1. Log-binned slope-area data points were plotted using a logarithmic scale on both axes. Linear regressions were fit for data points downstream from $A_{cr}$. $k_s$, steepness index, and concavity index, $\theta$, can both be determined from these linear regressions (equation 1).

**Identification of Knickpoints and Knickzones**

Slope-area plots and longitudinal profiles were used to identify knickpoints in all of the analyzed streams. Knickpoints can be identified as clear breaks in the slope-area relation on a log-log plot. A knickpoint (and its corresponding knickzone) is defined as migratory if it maintains its relative form and moves in a headword direction through time (Wobus et al., 2006). If a knickpoint (and its knickzone) is migratory then it must have a downstream source of base-level fall and a causative mechanism of base-level fall. Additionally, there must be sufficient drainage area (and therefore discharge) for the knickzone to incise and propagate upstream. Channel substrate must also be competent enough to uphold a relatively steep gradient. Possible causative mechanisms of base-
level fall include differential tectonic uplift and eustatic sea-level change. In contrast, stationary knickpoints remain in one location over time and can be caused by transitions between lithologies of differing resistances or deposits of large erosionally resistant substrate (usually from mass wasting events) in the channel that impede incision (Seidl and Dietrich, 1992).

Knickpoints were analyzed based on their location relative to lithologic contacts and large-scale landslides and their relation to strath surfaces in upstream and downstream reaches. In multiple cases knickpoints were located near lithologic contacts, which led to questions about differences in lithologic resistance across lithologic contacts. If a river is incising uniformly in a given reach then the profile of the strath surface(s) in the reach should parallel that of the river. If a knickzone is actively migrating upstream then the lowest strath surface will become more vertically separated from the modern channel only after the knickzone has migrated past a certain location. This relationship will produce a divergence in the downstream direction of the modern profile with the lowest strath surface along the knickzone. Knickzones that exhibited this relationship were tentatively considered migratory and further investigated for possible causative mechanisms.

USGS 7.5’ topographic maps and the 10 m DEM-derived hillshade model were used to investigate knickpoints that were potentially the result of major landslide deposits. Landslides of varying sizes are present throughout the basin. In multiple locations, relatively smaller (0.01-0.1 km²) active landslides occur along the immediate channel and produce minor, stationary knickpoints in the form of a single rapid. We
attempted to locate and map deep-seated, large-scale landslides that can be up to an order of magnitude or more larger than the more common smaller slides. Such large-scale landslides are capable of producing a major knickpoint and knickzone affecting hundreds to thousands of meters of channel length.

**Projecting Longitudinal Profiles**

Projecting an upstream longitudinal profile beyond a migratory knickpoint can be revealing of the surface or elevation that the relict (i.e. upstream of the knickpoint) portion of channel is graded to in the downstream direction. Longitudinal profiles for select streams were projected using an Autoregressive Integrated Moving Average (ARIMA) time series model. In this model, X, the distance from the mouth, is interpreted to be the time component of the time series analysis. ARIMA is a dynamic model that assumes dependence in adjacent pairs of observations (Ramsey and Schafer, 2002) and in this case a pair of observations is two adjacent elevations along the stream profile. The ARIMA model is appropriate because if you consider one elevation on a stream then the next adjacent elevation should have a similar value because they are next to each other. ARIMA models are designed to predict (i.e. project) data points beyond the extent of the series.

**Lithologic Resistance**

Lithologic resistance is a control on incision and therefore on channel profile evolution. Factors influencing lithologic resistance include intact rock strength and the spacing of joints, or bedding planes, within rock outcrops. If bedrock exposures of
different lithologies are directly exposed to moving water within the channel, harder rock
with larger joint spacing will resist erosion by abrading and plucking more effectively
than softer rock with smaller joint spacing (Snyder et al., 2003).

The Schmidt hammer was used to measure the in situ bulk rock strength of
bedrock exposures along the immediate channel sides. The Schmidt hammer rapidly
measures the energy rebounded by a rock when impacted, with a larger rebound from
harder rock. The sampling design covered each lithologic unit along the mainstem Smith
and the Middle and South Forks. In headwater reaches of the Middle and South forks,
sampling became difficult to impossible due to limited access and lack of exposed
bedrock in the active channel.

All measurements were taken within the active channel as close to the river as
possible. At each site, 15-20 measurements were taken with the Schmidt hammer with
spacing between points of no less than 10 cm. The Schmidt hammer was always held
perpendicular to the rock surface. Measurements were taken using an “integrated”
sampling method (described by Lifton et al. (2009), Appendix A.) that distributes the
location of rebound measurements randomly across the outcrop. This approach
represents a measure of the rock bulk strength, which incorporates joint density and the
strength of the rock defined by these joints.

Joint spacing was measured at every Schmidt hammer-sampling site using a
metric tape with millimeter precision. Fifteen to 20 joint spacing measurements were
taken at each site. In locations where multiple joints defined a bedrock block, the
intermediate axis joint was recorded. In most lithologic units, jointing appeared to be the
only feature that separated individual bedrock blocks. However, in many locations within the Galice Formation, original bedding is still preserved and spacing between beds and joints were measured. Bedding and jointing are effectively the same because flowing water will pluck equally blocks defined by either joints or bedding.

A statistical analysis was used to test the hypothesis that rock strength differs among lithologic groups. The hypothesis was tested using a single-factor Analysis of Variance (ANOVA) in which the factors were lithologic groups (Franciscan/metasedimentary, Galice/slate, metavolcanic, diabase, gabbro, and peridotite). Sequential sums of squares were used to test for the main effects of rebound value first and then the interaction effect of joint spacing because joint spacing also affects rock strength among lithologic groups. The statistical model uses the average joint spacing value of the entire data set to compute means of Schmidt hammer rebound for each lithology (i.e. group).

RESULTS

Dependence of Rock Strength on Lithology

Schmidt hammer rebound (B) plotted versus joint spacing (Figure 4) shows the wide range of physical rock strength properties measured throughout the watershed. Data points grouped on lithology all show a similar positive correlation. ANOVA calculates the average Schmidt hammer rebound value for each lithology at the mean joint spacing value of 20.34 cm (Figure 4).
Schmidt hammer rebound varied significantly among lithologic groups (P<0.001). Rebound was significantly higher for metavolcanic, diabase, and peridotite compared to Franciscan metasedimentary rock (Figure 5). The Galice Formation data, by contrast, had an exceptionally large confidence interval (+/- two standard errors) and thus did not have a statistically significant variance from any other unit, however it is clear qualitatively that Galice Formation rocks have the lowest rebound value (Figure 5).

The three reasons that the Galice Formation has a large confidence interval are the number of measurements, n, in the Galice is relatively small, the majority of rebound data points are clustered at the low end of joint spacing (i.e. below the mean of joint spacing, the point at which group comparisons in rebound are made) (Figure 4), and the Galice exhibits the greatest variability in Schmidt hammer rebound. In the field, the Galice is typically manifest as a fissile unit with millimeter-centimeter spacing between beds and joints. In few locations the Galice is more massive and competent with a metagreywacke and metavolcanic component. Because n is relatively small it is possible that the Galice Formation does have outcrops with higher joint spacing, and therefore we cannot preclude the possibility that the Galice would follow the same trend (in Schmidt hammer rebound (B) versus joint spacing, Figure 4) as the other units.

Because of the clustering of data points at low joint spacing and rebound, the residuals in the ANOVA were slightly left skewed and had higher variance at the low end of rebound values. As alternatives, the ANOVA was also performed with the Galice data omitted and with squaring the response variable, rebound (B), to correct the residuals. In both cases this made no difference compared to the original results (i.e. Figure 5),
indicating rebound is significantly higher for metavolcanic, diabase, and peridotite compared to Franciscan rocks.

**Stream Profile Analysis**

Results of the DEM analysis are organized into composite longitudinal profiles grouped on sub-basins (Figures 6, 7, and 8) and individual slope-area plots of each stream analyzed (Figure 9). Longitudinal profiles and slope-area plots show that knickpoints are abundant throughout the major forks and tributary creeks in the basin. Linear regression of slope-area relations for drainage areas greater than $A_{cr}$ yields concavity and steepness indices for each analyzed stream (Figure 9). The reference concavity ($\theta_{ref}$) for the Smith River watershed, which is the average of the individual concavity indices of the North, Middle, and South Forks, is 0.52. The $\theta_{ref}$ was used to calculate normalized steepness indices ($k_{sn}$) for the three major forks (Table 1).

**Terraces**

**Terrace Stratigraphy and Surveying**

Fluvial strath terraces, identified from aerial photos, 1 m DEMs, and fieldwork, are present throughout the Smith River watershed (Figures 10, 11, and 12). Strath terraces typically consist of alluvial fill overlying a bedrock strath surface; however, in some locations strath surfaces are exposed without a cap of alluvium (Figure 13). Alluvial fill thickness, which was measured along road cuts and cutbanks, averages 5.2 m and ranges from no alluvial cover up to approximately 11.0 m. RTK surveyed elevations represent the surface of the alluvial fill that overlies the strath surface. However, in a few
locations on the Middle Fork, strath surfaces were directly accessible to measure with the RTK receiver. Terrace elevations obtained from the LiDAR-based 1 m DEM represent the alluvial fill surface.

Terrace elevations were plotted on longitudinal profiles of the Middle and South Forks using a custom MATLAB code (Figure 14). The code projects RTK data points perpendicularly to a channel centerline by minimizing the distance based on northing and easting values of both data sets. Terrace elevations are grouped, based on relative elevation above the stream profile, into two different terrace flights (Figure 14). One terrace flight is downstream of the Middle Fork and South Fork gorge knickzones and the other is upstream (Figure 14). Two different terrace flights were designated because terraces located on the upstream and downstream sides of the Middle and South Fork gorge knickzones cannot be systematically correlated based on vertical spacing or relative elevation above the stream profile. The two different terrace flights each consist of five individual terrace tread surfaces but the relative vertical spacing and elevation above the modern channel is different among the two flights (Figure 14).

To tie the RTK surveyed terrace elevations into river channel elevations of the same degree of accuracy, channel water surface elevations were also RTK surveyed in many locations (Figure 14). All RTK surveys were conducted over a three-week period in late summer when changes in river stage are negligible. In multiple locations the RTK surveyed water surface elevation points do not agree with the 10 m DEM based longitudinal profiles. While all measurements downstream of approximately river kilometer 36 (on the Middle and South Forks) do agree with the 10 m DEM long profiles,
measurements upstream of river kilometer 36 (on the Middle and South Forks) do not. Some RTK surveyed water surface elevations plot above the 10 DEM profile and some below (Figure 14). RTK surveyed elevations have a better vertical accuracy (+/- approximately 0.05 m) than water surface elevations computed from the 10 m DEM’s. Where RTK water surface elevation measurements were available, they were used rather than the 10 m DEM elevations. By doing so, we eliminated several 10 m DEM-based “stair-step like” artifacts in the longitudinal profiles, which can give the false appearance of a knickpoint (Figure 14). Where appropriate, we used RTK elevation data to reconstruct longitudinal profiles for the Middle Fork and South Fork (Figure 14).

Along the Middle Fork and South Fork gorge knickzones, the lowermost elevated strath surface shows a distinct divergence from the modern river profile in the downstream direction (Figure 14). Strath surface elevations along the two knickzones were measured relative to the water surface elevation using a pocket transit level (Figure 14). The deep, narrow gorge walls along the knickzones inhibited satellite contact and therefore precluded accurate elevation results using the RTK. Redundant surveys using a stadia rod indicate that the pocket transit level surveys have a vertical accuracy of approximately 5 cm. Along the Middle Fork and South Fork gorge knickzones, strath surface treads are narrow (3-10 m) and are either barren of alluvial fill or have up to 3-m-thick fill deposits in a few locations. Longitudinal profiles of these gorges generated from 10 m DEMs, 7.5’ USGS topographic quadrangles, and field surveys agreed within a vertical resolution of 2-5 m and a horizontal resolution of approximately 5-10 m.
**Terrace Distribution**

Mapped strath terraces upstream of where the Smith River exits its canyon setting and flows onto the Crescent City coastal plain (at approximately river kilometer 10) were compared with bedrock geologic mapping in ArcMap to determine terrace spatial distribution relative to lithology (Table 2). The terrace spatial distribution analysis did not include terraces downstream of where the Smith River flows onto the Crescent City coastal plain because these significantly larger terraces are not bounded by bedrock hillslopes. The length of channel in each lithologic unit from river kilometer 10 to the upstream extent of mapped terraces (on the Middle and South Forks) was also compared to bedrock geology (Table 2). Upstream of river kilometer 10, a total of 220 remnant terrace surfaces were mapped. Peridotite, Galice, and Franciscan lithologies contain the most individual terrace remnants and encompass the largest terrace areas (Table 2). These same lithologies populate most of the length of the channels analyzed. Peridotite has the most mapped terrace surfaces, 87, and is the most abundant lithology along the river channel with 42.27 river kilometers of exposure within the area of mapped terraces. The Galice Formation has the second longest exposure along channel lengths, 25.1 river kilometers, and the second highest number of mapped terraces, 56. The most expansive terraces, with a total mapped area of 6.852 km², occur in the Franciscan Complex rock in the lower watershed. Franciscan rock is relatively weaker than the ophiolitic rocks and therefore optimally susceptible to lateral corrasion. The resistance of rock to erosion, as measured by Schmidt hammer rebound, does not appear to be a major factor in whether terraces form or not because peridotite is both the most abundant terrace former
(measured by number of remnant terrace surfaces) and one of the lithologies most resistant to erosion (Table 2).

**Knickpoints and Knickzones**

Knickpoints and knickzones are present along the main forks and tributary creeks throughout the Smith River watershed (Figures 6-8). Knickpoints are the distinct upstream point of an oversteepened reach, termed the knickzone (Foster and Kelsey, 2012). Knickpoints in the Smith River do not exhibit a vertical face consisting of a resistant caprock and less resistant subcaprock (e.g. Haviv et al., 2010). Caprock-subcaprock knickpoints are precluded by the underlying geology consisting of Franciscan sandstone and shales, Galice slate and metasediments, the Josephine ophiolite sequence, and various metavolcanic rock, all of which are folded and faulted. Although some minor waterfalls occur where water flows over very large boulders or local anomalously resistant bedrock, they are not the result of undeformed, horizontally stratified beds with varying resistance.

Two major knickzones (the Middle Fork and South Fork gorges) are located on the Middle Fork and South Fork just upstream from the confluence of these forks (Figure 14). Both knickzones are similar based on position, elevation, and morphology (Table 3). The Middle Fork and South Fork gorge knickpoints lie at 30.3 km and 29.3 km upstream, respectively, of the river mouth. The knickpoints occur at approximately the same elevation, 47.7 m on the Middle Fork and 50.2 m on the South Fork. Throughout their knickzones the Middle Fork drops 12.5 m in 0.8 km while the South Fork drops 14.3 m in
1.1 km. Both knickzones flow through peridotite and diabase, which do not have a significant difference in rock strength, and both knickzones are channels incised into bedrock with discontinuous deposits of coarse boulders on the bed (Figure 15). The bedrock channel banks rise vertically to subvertically to strath surfaces that are 13-16 m above the channel at the downstream extent of the knickzones (Figure 14).

Multiple major knickpoints are located in upstream and headwater reaches of the Middle and South Forks. Major knickpoints located at river kilometers 59 and 76.5 on the South Fork (Figure 16C) and 75 and 80.5 on the Middle Fork (Figure 19C) are the consequence of large-scale landslides that have mobilized entire hillslopes into the channel. Large-scale landslide deposits along channel banks were investigated in the field and consisted of boulder to house-sized blocks entrained within a poorly sorted fine matrix. Deposits affected hundreds to thousands of meters of channel length that are manifest as cascades, waterfalls, and pool-drop sequences.

The knickpoint located at river kilometer 59 on the South Fork occurs at the upstream end of a large-scale landslide deposit (Muslatt Slide) on the west slope of Muslatt Mountain (Figure 16). Muslatt Slide is a deep-seated landslide composed of the entire hillslope (from ridge top to river channel, ~850 m of relief) that was identified from a 10 m hillshade model, topographic maps, and existing geologic databases. The slide is located completely within the Galice Formation and is a rotational and translational debris slide with a large actively eroding toe rising approximately 133 m above the modern channel (Figure 16). At the apex of the headscarp of the slide is a
prominent bedrock wall, below which lies a small lake (Muslatt Lake) formed in a
depression behind a block that has back-rotated due to the slide (Figure 16A).

Approximately 10.7 km upstream of Muslatt Slide is a minor knickpoint (Figure
17) with anomalously large flat surfaces (identified on 7.5’ topographic maps, 10 m
hillshade models, and aerial photographs) bordering the knickzone in the immediate
downstream reach. These anomalous surfaces lie at the same exact elevation as the top of
the active toe of Muslatt slide. The flat surfaces are delta deposits that grade upstream to
alluvial fill deposits (Figures 17 and 18). The delta deposits have a minimum thickness
of 2-3 m and consist of poorly sorted sand and gravel. Such deposits are rare along the
Smith River except for in the extreme lower watershed or locally in the downstream side
of large outcrops where eddies form in high flow. The alluvial fill deposits, which are
immediately upstream of the delta, are a minimum of 5-5.5 m thick and consist of matrix-
and clast-supported gravels with an average clast size of 15-20 cm. Total thickness of the
alluvial fill cannot be determined because a bedrock strath surface is below channel level
(Figure 18). We infer that these delta and fill deposits were deposited at the upstream
extent of a paleolake created by a landslide dam located where Muslatt Slide deposits
infilled the South Fork canyon (Figure 17). The minor knickpoint located 10.7 km
upstream of Muslatt Slide is a result of post-dam-breach incision by the South Fork River
through the fill and delta deposits. The modern day South Kelsey Trail extends along the
same reaches as did the paleolake, hereinafter referred to as South Kelsey Lake. South
Kelsey Lake had an area of 3.8 km² (Figure 17) and a maximum depth of 133 m on the
upstream side of the dam.
The knickpoint at river kilometer 80.5 on the Middle Fork (Figure 19C) is produced by Broken Rib Slide, which is located on the northern slope of Broken Rib Mountain (Figure 19A and 19B). Similar to Muslatt Slide, Broken Rib Slide is a rotational and translational debris slide composed of the entire hillslope. The slide is located within a metavolcanic unit of the Rattlesnake Creek Terrane of the Western Paleozoic and Triassic Belt (Irwin, 1972). The knickzone is manifest as a steeply descending set of cascades and waterfalls flowing through very coarse slide deposits (Figure 20). The slide deposits along the immediate channel were previously mapped as glacial moraines and outwash (Wagner and Saucedo, 1987). Although there are a few minor glacial cirque features along the drainage divide at 1,750-1,900 m, there is no evidence of enough ice to produce the volume of sediment contained within Broken Rib Slide; and it is doubtful that any cirque glaciers extended down to approximately 1000 m, the elevation of the slide deposits.

**Paleolongitudinal Profile Projections**

Using an ARIMA model, paleolongitudinal profiles were projected downstream of the major knickpoints located at the upstream end of the Middle Fork and South Fork gorge knickzones (Figure 21) in order to evaluate whether relict channels, which predate the knickzones, project downstream to uplifted marine terrace surfaces. The confluence of these two forks is approximately 2-3 km downstream of their respective knickpoints (Figure 14). Channel elevations upstream of the Middle Fork and South Fork gorge knickpoints and downstream of the next major knickzone upstream in each fork (Figure
21B and 21C) were used as input observations for the ARIMA analyses. The input observations consisted of both RTK surveyed channel elevations and 10 m DEM channel elevations on both forks. Therefore, the two forks serve as two different input data sets to project relict channel profiles towards the mouth of the river.

To test whether the relict channel profiles project to a base-level defined by the oxygen isotope stage (OIS) 5e marine terrace (last major interglacial highstand) (Shackleton and Opdyke, 1973) on the Crescent City coastal plain, we plotted RTK surveyed elevations of the stage 5e marine terrace on modern and projected profiles (Figure 21). Polenz and Kelsey (1999) map the highest marine terrace on the Crescent City coastal plain as Qpm1 and infer that the Qpm1 terrace could be either stage 5e (125 ka) or stage 7 (200 ka) in age. The age uncertainty is a consequence of the possibility that the stage 5e highstand may have reoccupied the stage 7 highstand platform along the stretch of coast that straddles the California-Oregon border (Kelsey and Bockheim, 1994). RTK surveyed elevations were taken on the top of the Qpm1 marine terrace (Figure 21A). The black dot on the projected profiles (Figure 21B and 21C) is the average of these elevation measurements (Table 4).

If the paleolongitudinal profile of the Smith River was graded to the OIS 5e sea level highstand, the profile would be graded to the back edge of the marine bedrock strath that marks the paleoshoreline at the time of the highstand (Figure 21A). The modern day elevation of the strath surface, which is in the range of 16-28 m (green vertical bar in Figure 21B and 21C), is the difference between the average RTK-determined elevation of the marine terrace surface and the thickness of the cover sediment that separates the
surface from the underlying strath (Table 4). The range of possible marine cover sediment thicknesses in the vicinity of the paleoshoreline (3-15 m) (Table 4) is similar to the range of cover sediment thickness estimates for marine terraces of the same age at Cape Blanco, Oregon, 115 km to the north (Kelsey, 1990).

**DISCUSSION**

**Inferring Tectonic Uplift from Stream Profiles**

Stream profile analyses along the major forks of the Smith River watershed lend insight to the uplift rate gradient in the upper plate of the subduction zone across the Smith River basin. The Smith River watershed lies above the megathrust of the Cascadia subduction zone (Figure 1). Marine terraces on the Crescent City coastal plain at the west end of the Smith River basin are deformed into open folds. OIS 5e marine terraces have maximum uplift rates of 0.3 mm/yr (Polenz and Kelsey, 1999), but tectonic uplift rates further inland in the Smith River watershed remain unknown.

River basin morphometry, however, is a basis for inferring that there is a gradient in uplift rate with increasing uplift rate corresponding to greater distance perpendicularly inland from the Cascadia margin. Because there is a direct correlation between steepness index \( k_s \) and uplift \( U \) (equations 1 and 2), the range of \( k_{sn} \) values for the three major forks of the Smith River (Table 1) may track the distribution of tectonic uplift across the watershed. The North Fork watershed is oriented north-south and lies closer to the coast than the Middle Fork and South Fork watersheds (Figure 2). The Middle Fork and South Fork watersheds are both oriented east-west and extend further inland compared to the
North Fork watershed. The $k_{sn}$ value for the North Fork is the lowest of the three at 65.30. The $k_{sn}$ values for the Middle Fork and South Fork are 73.43 and 83.79, respectively.

We infer that, based on $k_{sn}$ values, the North Fork is in a coastal area with lower uplift rates compared to the Middle Fork and South Fork that are further inland and experience higher uplift rates. While these comparisons do not quantify the uplift rates across the Smith River basin, they do provide insight that the outer forearc above the subduction zone has greater surface uplift rates going further inland from the coast to the headwaters of the Smith River basin (a coast-normal distance of 46 km) as the underlying subduction zone deepens from 16 km to 27 km depth (McCrory et al., 2006) (Figure 1).

**Paleolongitudinal Profiles Project to Marine Terraces**

The Middle Fork and South Fork gorge knickpoints/knickzones are comparable in elevation, slope, length, and distance upstream. Based on strath surface elevation relationships in upstream and downstream reaches of the gorge knickpoints (Figure 14), we infer that these knickpoints are migratory and we address the question of what was the knickpoint initiation mechanism. Paleolongitudinal (relict) profiles of both forks project to the Qpm1 marine terrace (OIS 5e and/or 7) preserved on the Crescent City coastal plain near the mouth of the Smith River (Figure 21). The projected profile of the South Fork intersects the middle of the range of possible strath surface elevations for the Qpm1 marine terrace. And the range of possible strath elevations for Qpm1 is entirely contained within the 95% prediction interval of the projected profile. The relict profile
projection using the Middle Fork data follows a similar trend, although the projection intersects the range of possible marine strath elevations at its lower end.

If base-level rapidly fell following a drop in eustatic sea level from a sea level highstand and initiated a knickpoint, then the South Fork and Middle Fork gorge knickpoints have migrated approximately 17 km upstream from the former shoreline to their present locations. Using the 200 ka age assignment of the Qpm1 marine terrace (OIS 7) yields a knickpoint migration rate of 85 mm/yr while using the 125 ka age (OIS 5e) assignment yields a migration rate of 136 mm/yr. Loget and Van Den Driessche (2009) compare a suite of migrating knickpoints propagating through bedrock channels from 5 different rivers in France and Spain. These rivers all have comparable drainage areas to the Smith River and have knickpoint migration rates that range from 80 mm/yr to 400 mm/yr, encompassing the range of possible migration rates on the Smith River.

**Elevation Grouping of Migratory Knickpoints**

A knickpoint migrating up a trunk stream will also migrate up tributaries once the knickpoint has propagated past the outlet of a tributary. Migratory knickpoints propagate more quickly along higher order channels because they have a higher drainage area and propagate more slowly along lower order channels with less drainage area; as a consequence, migratory knickpoints initiated by a common mechanism tend to occur at similar elevations (Niemann et al., 2001; Wobus et al., 2006). In a comprehensive study of knickpoints in Tibet, Harkins et al. (2010) also found that knickpoints occur at similar elevations regardless of drainage area. The migratory knickpoints at the upstream end of
the Middle Fork and South Fork gorge knickzones are at the same elevation as prominent knickpoints in Mill Creek and Rowdy Creek, which are the only two large tributaries that lie downstream of the Middle Fork/South Fork confluence (Figure 22). Several other small tributaries (first and second order intermittent streams) were omitted because knickpoint identification on such small streams using 10 m DEM based profiles was unreliable. We infer that the knickpoint on Mill Creek was initiated at its mouth in the wake of the migrating knickpoint passing by on the mainstem Smith River, which triggered a tributary knickpoint that subsequently propagated up Mill Creek. If the original knickpoint on the mainstem Smith River was initiated as a result of a fall in base-level caused by a drop in eustatic sea level, then the correlative knickpoint on Rowdy Creek would have been initiated at the same time because Rowdy Creek would have flowed directly into the Pacific Ocean at the time of either the OIS 5e or 7 eustatic sea level highstands. Today, Rowdy Creek is tributary to the mainstem Smith River in the lowermost reaches at approximately river kilometer 5. The observation that knickpoints on the Middle Fork, South Fork, Mill Creek, and Rowdy Creek all occur at the same elevation supports the inference that these knickpoints are migratory and were initiated from a common event of base-level lowering.

**Drainage Area-Dependent Knickpoint Generation Mechanisms**

Knickpoint generation can relate to tectonics, lithology, or climate (i.e. hillslope processes or eustatic sea level change), and knickpoints may be either migratory or stationary (Leopold et al., 1964; Knighton, 1998). In the Smith River watershed there
appears to be a bimodality in knickpoint generation mechanisms. Knickpoints and their respective knickzones can be classified as migratory or stationary based on their position within the basin. In lower reaches of the watershed where drainage area is large, the two major knickpoints (Middle Fork and South Fork gorge knickpoints) are migratory. We infer that these knickpoints were generated at the mouth of the river from a base-level fall following relative sea level fall from a sea level highstand. The two migratory knickpoints lie just upstream of the confluence of their two forks, and drainage area decreases by approximately a factor of two when moving upstream from the mainstem onto either the Middle Fork or South Fork. Knickpoint propagation may stall due to a decrease in stream power associated with an abrupt decrease in drainage area above a stream confluence (Crosby and Whipple, 2006). The decrease-in-drainage-area internal control may explain why more migratory knickpoints are not seen further up-basin in either the Middle or South Fork. And the lack of additional migratory knickpoints upstream in either fork is not contradictory to multiple events of base-level fall at the mouth of the Smith River. If migratory knickpoints stall when drainage area becomes too small to promote further incision, then the Middle Fork and South Fork gorge knickzones could contain a composite of multiple stalled major knickzones.

In middle to upper reaches of the watershed where drainage area is smaller, major knickpoints are stationary and result from large landslides. Such large landslides induced two major knickpoints on the Middle Fork and two major knickpoints on the South Fork (Figures 16 and 19). Numerous other knickpoints in the basin located on tributary creeks (Figures 6, 7, and 8) have also been attributed to large landslide features. Topography and
lithology both are controls on the formation of these large landslides. Two of the slides (Muslatt Slide on the South Fork and another unnamed slide on the Middle Fork) occur within the Galice Formation, which has the weakest rock strength within the basin (Figure 4). Another unnamed large landslide upstream of Muslatt Slide on the South Fork occurs in an argillaceous siltstone unit within the ophiolitic mélange of the Rattlesnake Creek Terrane of the Western Paleozoic and Triassic Belt. The ophiolitic mélange of the Rattlesnake Creek Terrane is a structurally incompetent rock with an abundance of landslide features (Irwin, 1972). The remaining large-scale landslide (Broken Rib Slide) in the very upper Middle Fork basin also occurs within the ophiolitic mélange of the Rattlesnake Creek Terrane.

Topography is also important for generating large ridge-to-valley-bottom landslides because sufficient relief is needed to provide enough source material to deliver whole hillslopes to the active channel. The mélange of the Franciscan Complex is also an unstable unit characterized by large landslides (Aalto, 1989). But in the Smith River watershed Franciscan rocks only occur along the coast in the lower most part of the basin. Here topography is of low relief and therefore does not have the potential to produce landslide features that are capable of altering stream profile development. We infer that the combination of unstable lithology in areas of high relief in the upper portions of the Smith River watershed provide the conditions needed to deliver large quantities of landslide debris to channels that impede incision and thereby generate permanent knickpoints.
Terraces Record Events of Incision, Lateral Planation, and Base-level Lowering

Strath terraces on the Middle and South Forks of the Smith River comprise an upper basin flight of terraces (UT, Figure 14), and strath terraces downstream of the Middle and South Fork gorge knickzones on the mainstem below the confluence of these two forks comprise a lower basin flight of terraces (LT, Figure 14). The upper and lower basin terrace flights are different with regards to both terrace vertical separation and elevation above the modern channel. Therefore, it is not possible to correlate flights of upper basin terraces to flights of lower basin terraces across the two gorge knickzones (Figure 14).

Correlated terraces for the UT flight, both on the South Fork and Middle Fork, have paleolongitudinal profiles that are parallel to the modern stream profile as constrained by RTK channel elevation measurements. Further, for both forks, any one correlated terrace remains at a constant relative elevation above the modern channel for more than 20 km and does not diverge or converge with the modern profile. In contrast, terraces in the LT flight, which are below the two gorge knickzones and downstream of the confluence of the two forks, diverge in elevation above the modern channel going in an upstream direction.

Strath terraces along the Smith River record multiple events of incision and lateral planation. Climatic forcing of runoff and sediment supply drives cycles of incision and lateral planation necessary for strath terrace formation (Pazzaglia and Brandon, 2001; Hancock and Anderson, 2002; Wegmann and Pazzaglia, 2002). A flight of fluvial strath terraces in the North Fork Elk River basin (approximately 120 km south of the Smith
River watershed) have been correlated based on age and vertical spacing to paleoclimate proxies in sediment cores taken from the northern California continental margin (Stallman, 2003). In the Smith River basin the anomalously large strath terraces of Big Flat (Figure 12), at the confluence of Hurdygurdy and Jones Creek with the South Fork, have been interpreted as climatic aggradation surfaces associated with late Quaternary glacial cycles in the headwaters of those basins (Adkins, 1996).

Correlative strath terraces throughout the Middle Fork and South Fork (UT flight of terraces on Figure 14) have a general consistency in vertical separation between the next lowest and next highest terrace tread and also have a consistency in elevation above the channel (Figure 14). We infer that repeated climate-related cycles of incision (sediment supply limited) and lateral planation (sediment transport limited) during ongoing tectonic uplift are responsible for the multiple straths of consistent vertical separation.

However, the lower terrace (LT) flight converges in the downstream direction toward an ocean base-level and diverges in the upstream direction with the lowest two terrace treads merging with the gorge knickpoints (Figure 14). We infer, therefore, that the lower portion of the watershed (i.e. downstream of the Middle and South Fork gorge knickzones) has periods of incision driven by base-level fall related to fluctuating ocean levels, and that each terrace tread is a separate instance of major base-level fall. This confounding external control explains why there is a large, distinct vertical separation (14-20 m) between the modern stream longitudinal profile and the first elevated strath surface in the reaches immediately downstream of the migratory Middle Fork and South
Fork gorge knickpoints. Further downstream of the migratory knickpoints are strath terraces that are not as vertically separated (only 4-8 m) from the modern profile. Two of these lower terraces have radiocarbon age assignments of 3,615 and 10,409 cal BP (Meyer, 2008), placing them in the Holocene and very latest Pleistocene. These terraces were formed after the migrating knickpoint had already propagated past their location.

Based on the above observations, we infer that the UT and LT flights of terraces never physically correlated and the mechanism that drives incision episodes is not the same above and below the Middle Fork and South Fork gorge knickzones. The channel reaches on the Middle Fork and South Fork that separate the UT flight of terraces from the LT flight of terraces include the two gorge knickzones (one on each fork) and associated knickpoints, and upstream reaches (approximately 6.5 km) of river with minimal to no strath terrace development. We suggested above that the two gorge knickzones each represent multiple stalled knickpoints due to the drainage area decrease above the confluence of the forks. Knickpoint stalling is one reason the lower flight of terraces cannot physically connect to the upper flight of terraces. The other reason is that the top-of-basin to downstream development of flights of strath terraces ceases to be operative when sediment supply is reduced. Supply of sediment decreases downstream as source tributaries become less frequent and by clast attrition as boulders and cobbles become easily transported pebbles and sand. Because the 6.5 km-long reach of river on both forks, which separates the UT flight upstream from the LT flight downstream, becomes sediment supply limited, the conditions that promote lateral planation of straths is never or seldom attained along the reach.
In summary, terraces along the mainstem Smith River and along the Middle and South Forks are elevated above modern channels because of 1,954 m of topographic relief that prompts channel incision above the ultimate base-level of the ocean. This topographic relief in part may be generated by late Tertiary and Quaternary tectonic uplift in the upper plate of the Cascadia subduction zone. But the driver of specific periods of incision, which alternate with periods of lateral planation, is different upstream and downstream of the Middle Fork and South Fork gorge knickzones. Upstream, the driver is climate change that causes fluctuations in delivery of debris shed off basin hillslopes. That is, upper basin incision is top-down-driven from variations in sediment delivery to channels downstream. Downstream of the two gorge knickzones, the driver of incision is climate-driven periodic base-level fall caused by fluctuating ocean levels. The lower basin incision, downstream of the two gorge knickzones, is bottom-up-driven from base-level changes that propagate upstream by knickpoint migration. The ocean fluctuations are caused by glacial-interglacial climate cycles that periodically store water as ice on continents and depress ocean levels. The climate-driven ocean level changes are ultimately the same cyclical driver of incision as the climate-related fluctuations in sediment delivery in the upper watersheds of the South and Middle Forks of the Smith River.

**CONCLUSION**

The major forks and tributary creeks of the Smith River watershed contain multiple major knickpoints and associated knickzones. Knickpoints are manifest as the
head of an anomalously steep reach in the river’s profile, the knickzone. Schmidt hammer analyses throughout the basin show that differences in rock strength across lithologic contacts are not a primary driver of knickpoint formation. Differences in rock strength among different lithologic units and spatial distribution of those lithologic units within the basin do, however, affect strath terrace distribution.

There is a drainage-area-dependent, bi-modality in knickpoint formation mechanisms. In lower reaches of the watershed there are two major knickpoints/knickzones creating the modern Middle Fork and South Fork gorges. We conclude that the Middle Fork and South Fork gorge knickpoints are migratory based on relative strath surface elevations in upstream and downstream reaches, paleolongitudinal profile projections, and no discernable difference in rock strength among lithologic units where the knickpoints occur. Paleolongitudinal profiles of the Middle and South Fork channels project to the stage 5e marine terrace on the Crescent City coastal plain suggesting that base-level lowering synchronous with sea level fall following late Pleistocene eustatic sea level highstands may have initiated retreat of knickpoints and corresponding incision in the Smith River basin. In middle to upper reaches of the watershed, in-channel deposits from deep-seated, large-scale landslides produce stationary knickpoints and may have temporary control on stream discharge in the form of landslide-dammed paleolakes.

Stream profile analysis shows that there are differing rates of tectonic uplift across the Smith River watershed. The gradient of tectonic uplift rate is oriented coast- (and Cascadia subduction zone) normal with rates of uplift increasing with further distance
from the Cascadia margin. Of the three major sub-basins in the Smith River watershed (the North, Middle, and South) the North Fork basin experiences relatively lower uplift rates because it is oriented north-south and lies closer to the coast. The Middle Fork and South Fork basins experience relatively higher uplift rates because they are oriented east-west and extend further inland.

Incision in the Smith River watershed occurs in two different scenarios that are dependent on location in the basin. Incision in the lower portion of the watershed (below the Middle Fork and South Fork gorge knickzones) is initiated at the mouth from eustatic base-level fall and proceeds upstream in the form of knickpoint migration. The major decrease in drainage area that occurs when moving from the mainstem onto either the Middle Fork or South Fork causes these migrating knickpoints to stall and accumulate a composite of multiple migrating knickpoints each associated with an instance of eustatic base-level fall. Incision in upper portions of the watershed is related to climate driven cycles that cause variations in sediment supply to upper basin channels which controls periods of lateral planation (i.e. strath cutting) and vertical incision. The upper terrace flights do not proceed down to connect with the lower terrace flight because in this mid basin location the river channels become sediment supply limited and the mechanisms for lateral planation cease to operate. Finally, tectonic uplift on the upper plate of the Cascadia convergent margin ultimately is the driver of incision through creation of topographic relief above sea level.
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TABLE 1. NORMALIZED STEEPNESS INDICES
BASED ON $\theta_{ref} = 0.52^*$

<table>
<thead>
<tr>
<th>Major Fork</th>
<th>Normalized steepness index ($k_{sn}$)</th>
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<tbody>
<tr>
<td>North Fork</td>
<td>65.30</td>
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<tr>
<td>Middle Fork</td>
<td>73.43</td>
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<tr>
<td>South Fork</td>
<td>83.79</td>
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* $\theta_{ref}$ = Reference concavity for the North, Middle, and South Forks of the Smith River.

TABLE 2. SPATIAL DISTRIBUTION OF TERRACES ACROSS LITHOLOGIC UNITS

<table>
<thead>
<tr>
<th>Lithologic unit</th>
<th>Number of mapped terraces*</th>
<th>Total terrace area (km²)</th>
<th>Average terrace area** (km²)</th>
<th>Length exposed along channel*** (km)</th>
<th>Mean Schmidt hammer rebound</th>
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</thead>
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<tr>
<td>Franciscan</td>
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<td>0.008</td>
<td>6.16</td>
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<tr>
<td>Gabbro</td>
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<td>0.195</td>
<td>0.020</td>
<td>6.28</td>
<td>64.0</td>
</tr>
<tr>
<td>Peridotite</td>
<td>87</td>
<td>4.393</td>
<td>0.050</td>
<td>42.27</td>
<td>66.7</td>
</tr>
</tbody>
</table>

* Defined as mapped individual terrace remnant surfaces.
** The average area of a mapped terrace remnant surface.
*** Lengths calculated from upstream of river kilometer 10 (where the river flows onto the Crescent City coastal plain) to the upstream extent of terrace mapping on the Middle and South Forks.
### TABLE 3. ATTRIBUTES OF MIDDLE FORK AND SOUTH FORK GORGE KNIKPOINTS AND KNIKZONES

<table>
<thead>
<tr>
<th></th>
<th>Knickpoint distance upstream* (km)</th>
<th>Knickpoint elevation (m)</th>
<th>Knickzone length (km)</th>
<th>Knickzone elevation change** (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle Fork Gorge</td>
<td>30.3</td>
<td>47.7</td>
<td>0.8</td>
<td>12.5</td>
</tr>
<tr>
<td>South Fork Gorge</td>
<td>29.3</td>
<td>50.2</td>
<td>1.1</td>
<td>14.3</td>
</tr>
</tbody>
</table>

* Distance is measured upstream of the river mouth.

** The difference in elevation of the upstream and downstream points in the longitudinal profile.

### TABLE 4. ATTRIBUTES OF THE HIGHEST MARINE TERRACE ON THE CRESCENT CITY COASTAL PLAIN

<table>
<thead>
<tr>
<th>Terrace name</th>
<th>Inferred age* (OIS 5e (125 ky) and/or OIS 7 (200 ky))</th>
<th>Ground elevation along projection line to modern channel (m)</th>
<th>Terrace cover sediment thickness (m)</th>
<th>Marine platform (strath) elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qpm1*</td>
<td>OIS 5e (125 ky) and/or OIS 7 (200 ky)</td>
<td>31**</td>
<td>3–15</td>
<td>16–28</td>
</tr>
</tbody>
</table>

* Marine terrace Qpm1 (Fig 21A) is OIS 5e and/ or OIS 7 (Polenz and Kelsey, 1999). OIS = Oxygen Isotope Stage.

** 31 m is the average of five RTK elevation measurements on Qpm1. Locations of elevation measurements on Fig 21A.
Figure 1. (A) Location map showing the tectonic setting of the Smith River watershed. (B) Cross section of plate tectonic framework underlying the Crescent City coastal plain and the Smith River basin. Cross section is schematic as indicated by the variable lengths and depths depicted on the section. Depths and locked/transition zone positions from Burgette et al. (2009).
Figure 2. Watershed map illustrating the dendritic drainage pattern of the Smith River basin. The Smith River consists of three major forks (the North, Middle, and South) and many tributary creeks. The 1,877 km² basin drains from a maximum elevation of 1,954 m on Bear Mountain at the headwaters of the South Fork to sea level on the Crescent City coastal plain near the California-Oregon border.
Figure 3. Geologic map of the Smith River watershed and surrounding area. Bedrock geology is compiled from a USDA Forest Service geodatabase (USFS, 2010) and marine terrace data from Polenz and Kelsey (1999). Fluvial terraces were mapped for this research. In middle and upper reaches the Smith flows through various units of the Jurassic Western Klamath Belt (including the Josephine Ophiolite sequence) and Western Paleozoic and Triassic Belt. In lower reaches the Smith flows through the Cretaceous Franciscan Complex and Quaternary marine and fluvial deposits.
Figure 4. Rock strength data plotted as Schmidt hammer value (B) versus joint spacing (JS). The data are grouped based on lithology. B and JS have a direct positive correlation. The ANOVA assigns group means of Schmidt hammer rebound (B) (in Figure 5) at the average JS for the entire data set.
Figure 5. Markers indicate group means of Schmidt hammer rebound (B) from different lithologic units in the Smith River basin. Results are derived from multiple comparisons from a single factor ANOVA. Bars indicate 95% confidence interval (+/- two standard errors) for testing null hypothesis that group means are equal. Nonoverlap of bars indicates a significant difference in means at $\alpha=0.05$. 
Figure 6. (A) Composite longitudinal profiles of the North Fork sub-basin. (B) Hillshade map showing the location of tributary creeks analyzed. Knickpoints are shown on longitudinal profiles and on the hillshade map.
Figure 7. (A) Composite longitudinal profiles of the Middle Fork sub-basin. Inset profiles show cluster of knickpoint occurrence in more detail. (B) Hillshade map showing the location of tributary creeks analyzed. Knickpoints are shown on longitudinal profiles and on the hillshade map.
Figure 8. (A) Composite longitudinal profiles of the South Fork sub-basin. (B) Hillshade map showing the location of tributary creeks analyzed. Knickpoints are shown on longitudinal profiles and on the hillshade map.
Figure 9. Slope-area plots for the three major forks and select tributary creeks. Crosses represent actual data points from the 10 m DEM, red boxes represent log-bin averages of those points. Vertical blue lines represent drainage areas at which knickpoints occur. The geographic location of each stream is shown in Figure 4. \( \theta \) (concavity index) and \( k_s \) (steepness index) are determined from linear regression of the slope-area relation. Regressions are bounded by \( A_{cr} \) (critical drainage area where colluvial processes transition to fluvial processes) and the confluence with the next higher ordered stream.
Hurdygurdy Creek (north fork trib)

\[ \theta = 0.55 \]
\[ k_{SN} = 109 \]

Diamond Creek (north fork trib)

\[ \theta = 0.48 \]
\[ k_{SN} = 108 \]

Jones Creek (south fork trib)

\[ \theta = 0.50 \]
\[ k_{SN} = 133 \]

Baldface Creek (north fork trib)

\[ \theta = 0.4 \]
\[ k_{SN} = 75 \]

Stony Creek (north fork trib)

\[ \theta = 0.31 \]
\[ k_{SN} = 124 \]

Chrome Creek (north fork trib)

\[ \theta = 0.35 \]
\[ k_{SN} = 88 \]
Figure 10. (A) Map showing locations of detailed terrace maps throughout the watershed. (B and C) Terraces downstream of the Middle Fork and South Fork gorge knickzones (located on map C) are designated Lower Terraces (LT) 0-5. The LT terrace flight does not correlate based on relative vertical spacing and elevation above the modern river profile with the UT terrace flight.
Figure 11. (A) Map showing locations of detailed terrace maps throughout the watershed. (B and C) Terraces upstream of the Middle Fork gorge knickzone (Figure 10 C) are designated Upper Terraces (UT) 0-4.
Figure 12. (A) Map showing locations of detailed terrace maps throughout the watershed. (B and C) Terraces upstream of the South Fork gorge knickzone (Figure 10 C) are designated Upper Terraces (UT) 0-5.
Figure 13. (A) Photograph of strath terrace in the Middle Fork gorge knickzone. Note the lack of alluvial fill. Backpack for scale. (B) Photograph of typical strath terrace with alluvial fill, located in the upper South Fork sub-basin. Fill is approximately 3 m thick.
Figure 14. Strath terraces surveyed using real-time kinematic GPS on the (A) Middle Fork and (B) South Fork. The channel longitudinal profiles are derived from 10 m DEM’s using geomorphTools (Whipple et al., 2007). RTK constrained longitudinal profiles (black line) are also shown overlying the 10 m DEM based profiles. Note: at river kilometer 27 is the confluence of the Middle and South Forks at which point they flow together as the mainstem. Channel longitudinal profiles of the (C) Middle Fork gorge and (D) South Fork gorge are based on USGS 7.5’ topographic maps and field verification of upstream and downstream extent of the knickzone. Black dot = strath elevation, blue triangle = relative Schmidt hammer “B” value. Note uniform rock resistance (Schmidt hammer measurements) on either side of, and within, the migratory knickzone. Lithology is plotted along the bottom axis.
Figure 15. Photograph looking downstream through the Middle Fork gorge knickzone showing vertical to sub vertical walls of bedrock. The bedrock wall at center left is approximately 12 m high. The South Fork gorge, not pictured, appears identical.
Figure 16. (A) Oblique aerial photograph of Muslatt slide in the upper South Fork Smith River. View looking northeast. (B) Annotated photograph shows the landslide head-scarp (orange), slide deposit (yellow), and the inferred extent that is now erosionally removed from the other side of the river (brown). The fluvial knickpoint (yellow dot) is located at the upstream extent of the slide deposit. The knickzone extends along the entire slide deposit. (C) Composite long profiles of the Middle Fork, South Fork, and mainstem Smith River. All major knickpoints (plus the minor delta knickpoint on the upper South Fork) are shown. The longitudinal extent of the paleo-South Kelsey Lake is also shown.
Figure 17. South Kelsey paleolake. South Kelsey Lake was formed when a large-scale landslide occurred on the upper South Fork (likely Holocene or late Pleistocene) on the west slope of Muslatt Mountain. The landslide mobilized the entire hillslope and thus dammed the South Fork Smith River. Supporting evidence for the paleolake is the existence of alluvial fill and delta deposits at the upstream extent of the then-existent lake along the South Fork Smith River.
Figure 18.  (A) Photograph of delta deposits at right of photo (behind dog). Deposit truncated by modern point bar development. Delta deposits consist of silt, sand, and gravel. (B) Delta deposits extended downstream for approximately 500 m from the minor delta knickpoint. Person and dog for scale. (C) Photograph of alluvial fill deposits located immediately upstream of the delta deposits. Alluvial fill deposits consist of boulders and cobbles in a sand and silt matrix. Note the lack of a strath surface below the deposits. Person at center for scale.
Figure 19. (A) Oblique aerial photograph of Broken Rib slide in the headwaters of the Middle Fork Smith River. View looking south. (B) Annotated photograph shows the landslide head-scarp (orange) and slide deposit (yellow). The fluvial knickpoint (yellow dot) is located at the upstream extent of the slide deposit. (C) Composite longitudinal profiles of the Middle Fork, South Fork, and mainstem Smith River. All major knickpoints (plus the minor delta knickpoint on the upper South Fork) are shown.
Figure 20. Photographs of the knickzone created by Broken Rib slide. (A) The knickzone is manifest as a steeply descending set of cascades and (B) waterfalls flowing over very large blocks deposited by the slide. No bedrock is visible in either photograph and was not seen in the field. Note the person and dog for scale in upper left corner of photo B.
Figure 21. (A) Hillshade map of where the Smith River flows onto the Crescent City coastal plain. The fluvial terraces lie relatively lower in elevation and truncate the marine terraces. Black dots on Qpm1 are the five RTK surveyed elevations used to determine the average terrace fill elevation in B and C. (B) Modern and projected (pre-incision) longitudinal profiles using the South Fork data set. The projected profile intersects the middle of the range of possible strath elevations for the Qpm1 (OIS 5e and/or 7) marine terrace. (C) Modern and projected (pre-incision) longitudinal profiles using the Middle Fork data set. The projected profile intersects in lower end of the range of possible strath elevations for the Qpm1 (OIS 5e and/or 7) marine terrace. Location of 15A on Figure 2.
Figure 22. Composite longitudinal profiles of Middle Fork, South Fork, Rowdy Creek, and Mill Creek. The migratory Middle Fork and South Fork gorge knickpoints group based on elevation with knickpoints on Rowdy and Mill Creeks suggesting all four knickpoints have a common initiation mechanism.
Appendix A – Geographic data attributes

Color aerial photographs (1:16,000) for the entire watershed were available. These photos were taken for the US Forest Service between the months of May and June 1975, and thus show the river in moderate to low flow conditions. Photos that contained portions of the mainstem, primary forks, and select major tributaries were reviewed using a stereoscope to identify and/or map terraces. Identified terraces were then digitized onto NAIP (National Agriculture Imagery Program) imagery in ArcMap 9.3.1. NAIP acquires aerial imagery of the United States at a 1 m ground sample distance with a natural color spectral resolution. The NAIP imagery in this location is from 2009 and was used as a base map throughout this research.

Multiple 10 m horizontal resolution digital elevation models (DEM) covering the entire watershed were downloaded from the United States Geological Survey (USGS) Seamless Data Warehouse. DEM’s were subsequently mosaicked in ArcGIS to create a single raster of the entire watershed.

A Light Detection and Ranging (LiDAR) derived DEM with 1 m horizontal resolution was available (from the National Park Service and Save the Redwoods League) for the entire area covered by the Jedediah Smith Redwoods State and Redwood National Parks. LiDAR is capable of penetrating the thick tree canopy of old growth redwoods and accurately measuring the ground surface with decimeter vertical resolution. In ArcMap, a hillshade model of the ground surface was created from the 1 m DEM, which allowed terraces to be mapped.
Appendix B – Real-time kinematic satellite positioning surveying

Terrace and water surface elevations were surveyed using real-time kinematic (RTK) satellite positioning technology. TOPCON GR-3 receivers were used, which involves setting up a base station unit and using a mobile “rover” unit to collect data points on terrace fill, strath, and water surfaces. The GR-3 is capable of receiving signals from the Global Positioning System (GPS) and Global Navigation Satellite System (GLONASS; the Russian equivalent to the American GPS) satellite constellations and giving position solutions with precisions that are typically 3.0 cm horizontal/5.0 cm vertical, or better. Terrace abundance, ease of access, and river canyons becoming too deep and narrow to accurately receive satellite signals dictated the upstream extent of RTK mapping.

RTK positions were post-processed using the proprietary software TOPCON Tools. Post-processing involved further refining positions using a “correction” from the National Geodetic Survey (NGS) Continuously Operating Reference Stations (CORS) network. Base station positions for every survey were submitted to the NGS Online Positioning User Service (OPUS). The position “corrections” returned by the NGS OPUS include a northing, easting, and orthometric elevation and were used to post-process all data points. “Corrections” from OPUS were in the range of several decimeters to a couple of meters. Data were then exported as shapefiles into ArcMap and overlain on mapped terraces and river channels providing high quality vertical resolution.