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Knickpoint and knickzone formation and propagation, South Fork Eel River, northern California

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ABSTRACT

The South Fork Eel River, northern California (United States), displays a prominent knickzone in its longitudinal profile that may represent a perturbation that is propagating upstream. We investigated two tributary basins (Standley and Bear Pen Creeks) located downstream from this major trunk-stream knickzone to document the presence of knickzones within tributary and subtributary streams and to explore their correlation to the South Fork Eel River knickzone. We utilized LIDAR (light detection and ranging) derived digital elevation models to identify more than 100 major knickpoints and knickzones along 103 streams within these 2 tributary basins. Major knickpoints are located at clear inflection points separating two reaches of concave-upward stream profiles. These knickpoints can be delineated at breaks in the regression relation of channel slope versus drainage area for these two tributaries. Using the slope-area relation, we recreate paleolongitudinal profiles to represent the pre-incision profile of main stem tributary channels, as well as the pre-incision elevations of subtributary outlets. Knickpoint distribution throughout the two basins indicates that the channels are responding to pulses of incision initiated through base-level fall along the South Fork Eel River. However, most of the major knickpoints identified do not correlate with the current, prominent knickzone along the South Fork Eel River. Rather, knickpoint distribution within the study area indicates that there have been multiple instances of base-level fall along the South Fork Eel River, each triggered by the upstream passage of knickzones that are no longer preserved in the South Fork Eel River profile.

INTRODUCTION

Base-level fall at the mouth of a drainage basin can initiate an upstream-propagating wave of incision (e.g., Gardner, 1983). The manner by which incision migrates up a stream channel is an observation fundamental to understanding the process of river base-level evolution, especially in bedrock-dominated channels. Such migrating incision can take the form of transitory knickpoints and knickzones (Seidl and Dietrich, 1992; Crosby et al., 2005; Wobus et al., 2006; Crosby and Whipple, 2006; Hayakawa and Oguchi, 2009). A knickzone is a locally high-gradient reach between lower gradient reaches (Hayakawa and Oguchi, 2006, 2009). The knickpoint is the distinct inflection point between a knickzone and an upstream, lower gradient reach (Seidl and Dietrich, 1992; Wobus et al., 2006; Crosby and Whipple, 2006). In addition to transient knickpoints, there are also stationary knickpoints, where an erosionally resistant substrate in the channel locally impedes incision.

We believe that a prominent knickpoint present on a trunk stream has propagated past multiple tributary junctions, initiating tributary response to a rapid drop in base level at each tributary confluence. The tributary response is manifest as knickpoints in the longitudinal profiles of these tributary basins. This study documents propagation of knickpoints into tributary basins. In the past such documentation required exhaustive field surveys; however, with the recent availability of LIDAR (light detection and ranging) data from which 1-m-resolution digital elevation models (DEMs) are produced, we can now observe detailed channel-incision response to base-level lowering. We select an ideal field setting for such an opportunity and utilize LIDAR data in two adjacent, similar-sized tributaries to document recent knickpoints and knickzones as well as geomorphic evidence of older instances of base-level lowering.

Our objectives were to compile an inventory of knickpoints on two tributaries and associated subtributaries of the South Fork Eel River in northern California, United States (Figs. 1 and 2) using LIDAR-derived DEMs, and then determine whether major knickpoints in the tributaries are correlative with the major knickpoint in the trunk stream. We discuss, based on knickpoint attributes and correlation, knickpoint formation and propagation.

STUDY AREA

The South Fork Eel River is a bedrock-dominated channel in northern California. The river's elevation ranges from ~30 m at the confluence with the main stem Eel River to 1350 m at the headwaters, near Laytonville, at the southeast portion of the South Fork Eel River basin (Fig. 1). This tectonically active region is within a 70-km-wide deformation zone defined by the right-lateral San Andreas fault zone, which separates the Pacific plate to the west from the North American plate to the east (Kelsey and Carver, 1988). The basin geology is dominated by sandstone and siltstone of the coastal and central belts of the Mesozoic Franciscan Assemblage, with relatively minor exposures of Franciscan Assemblage ultramafic rocks and late Neogene and Quaternary sediments (Strand, 1962; Jennings and Strand, 1960) (Fig. 1). The South Fork Eel River is distinctive because it has an extensive knickzone ~135 km upstream from its confluence with the main stem Eel River, between the tributary junctions of Rattlesnake and Ten Mile Creeks (Crosby and Willenbring, 2007) (Figs. 1 and 2). In addition, numerous knickpoints have been identified along tributaries of the South Fork Eel River using 10 m DEMs (Crosby and Willenbring, 2007). The knickzone along the South Fork Eel River is entirely within the coastal belt of the Franciscan Complex (Fig. 1) and does not appear to have a lithologic cause. Observations of other river systems (Kirby et al., 2003; Kirby
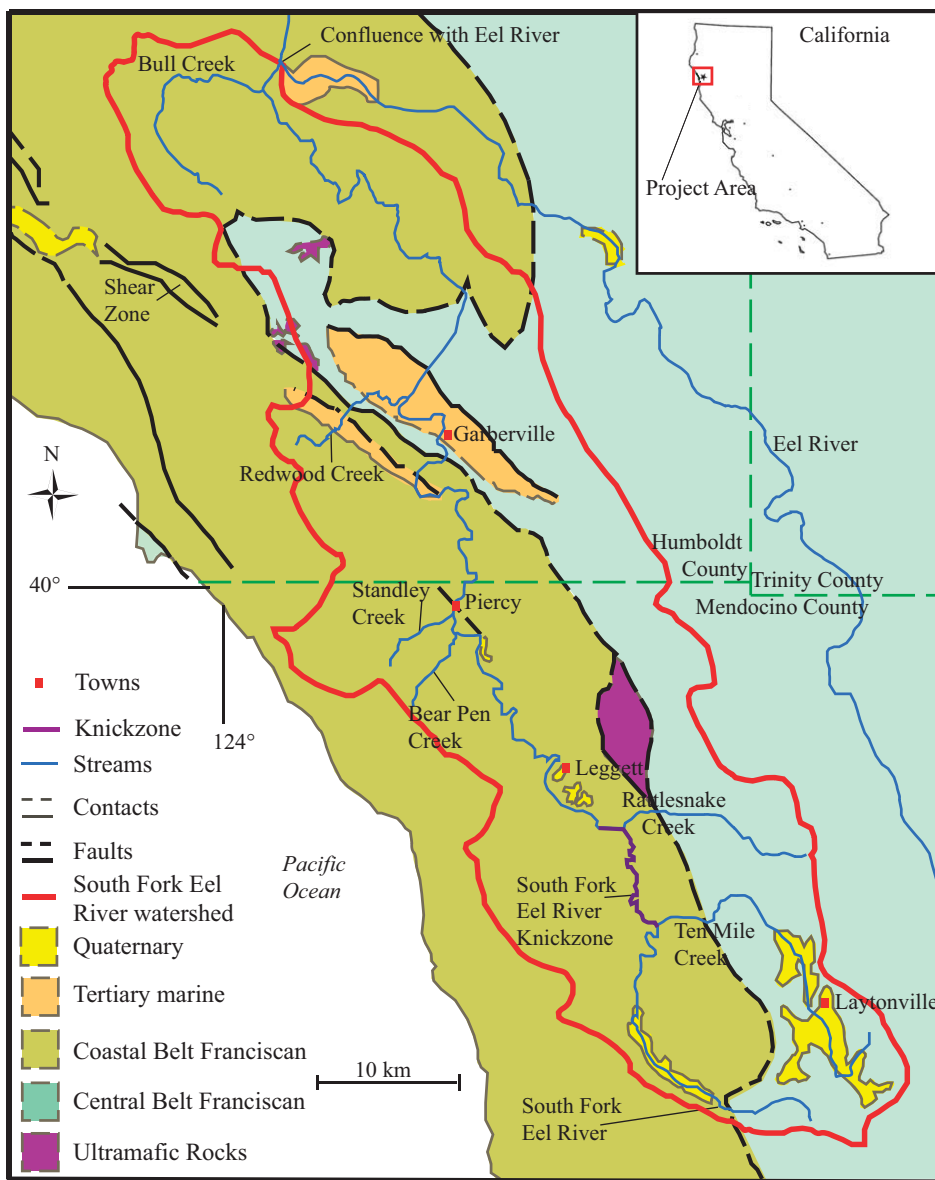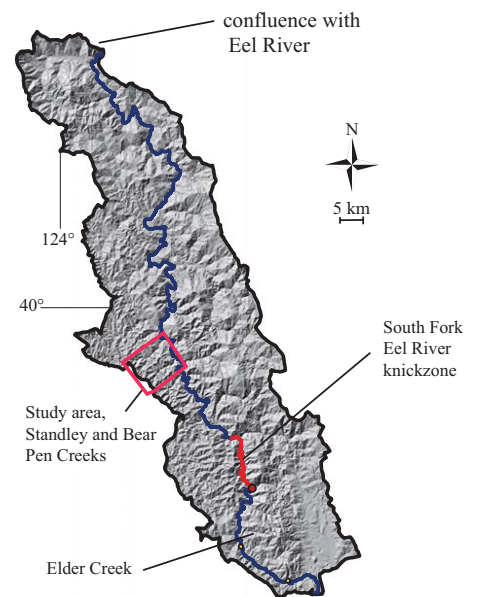
Figure 1. Location map of the South Fork Eel River basin in context of regional geology. Geology generalized from Jennings and Strand (1960) and Strand (1962) and slightly revised based on Kelsey and Carver (1988).

Figure 2. Hillshade map of the South Fork Eel River derived from 10 m digital elevation models (DEMs) and available 1 m DEMs. Red box delineates the study area and area of LIDAR (light detection and ranging) data acquired for this research.

RESEARCH APPROACH

Knickpoints and knickzones were identified from longitudinal profiles generated from 1 m DEMs. Major knickpoints were selected where the associated knickzone greatly deviates in gradient from the upstream reach and denotes a major shift in the longitudinal profile. Figure 3 is a schematic profile depicting knickpoint classification and profile features. Major knickzones may contain minor knickpoints, so identified if the trend gradient of the knickzone is not greatly affected by the minor knickpoint (Fig. 3). Data collected in the field, as well as aerial photo analysis, were used to verify major or minor knickpoint and knickzone locations. LIDAR-based DEMs were also investigated for terraces which could represent pre-incision channel longitudinal profiles.

LIDAR-Generated Digital Elevation Models for Longitudinal Profile Extraction

Although 10 m DEMs are effective in identifying large trends in river basins, analysis of knickpoints and knickzones in smaller tributary basins is made possible through the use of high-quality 1 m DEMs. In our study area many of the peculiarities observed in the fluvial network during field investigations were obscure on 10 m DEMs. Several first- and second-order stream

and Ouimet, 2011) also lead to inferences that steepened gradients along large trunk rivers may not be correlated with lithology.

Our research documents knickpoints within two basins tributary to the South Fork Eel River, Standley and Bear Pen Creeks (Fig. 1 and 2). This detailed study of knickpoints was made possible through high-quality 1 m DEMs produced from a 40 km² LIDAR acquisition; we selected this area for LIDAR acquisition because we could study two adjacent tributary basins downstream from the South Fork Eel River knickpoint. Because the area is entirely within the coastal belt of the Franciscan Assemblage (Fig. 1),

tributary longitudinal profiles and associated knickzones are not influenced by deep-seated earthflow landslides, which are characteristic of the mélange units within central belt of the Franciscan Assemblage (Kelsey, 1980).

Standley and Bear Pen Creeks (19 and 13 km², respectively) are adjacent bedrock-dominated tributary basins located near the town of Piercy, ~40 km downstream from the base of the South Fork Eel River knickzone (Fig. 1). Similar drainage network patterns within the two study basins provide an opportunity to compare two realizations of the propagation of a single knickpoint into tributary valleys.
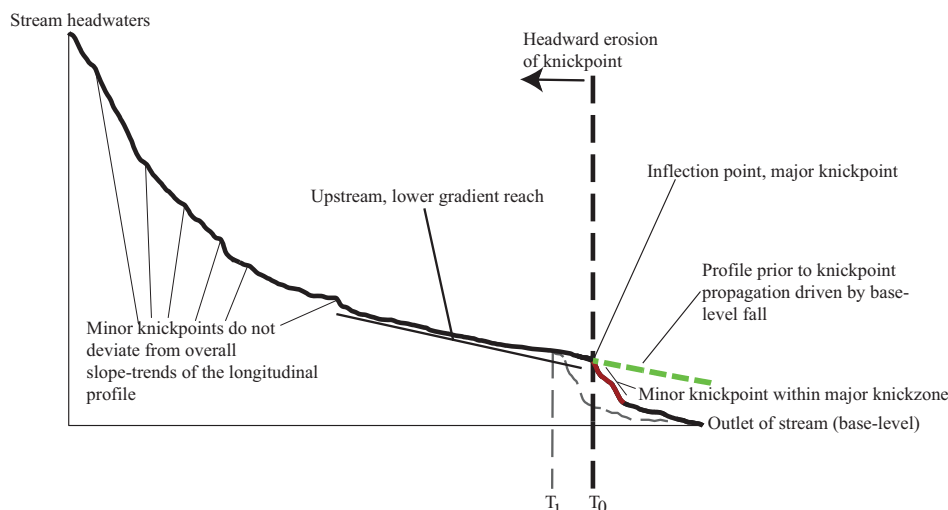
Figure 3. Schematic figure depicting knickpoints and knickzones. A knickzone is a high-gradient reach, surrounded by lower gradient reaches. A knickpoint is the inflection point between a downstream, high-gradient reach (knickzone) and an upstream, lower gradient reach. Note how the major knickpoint denotes a major shift in the slope-trend of the longitudinal profile, whereas the minor knickpoints do not. T_0 is the current major knickpoint position; T_1 is a possible future position of the major knickpoint with progressive incision. Knickpoints in the upper portion of the stream profile may indicate previous events of base-level fall, but are unrelated to propagation of a major knickpoint.

basins identified in the field are not present or are poorly defined on 10 m DEMs (Fig. 4). Also, large knickzones along subtributaries in our study area may only extend for 30–40 m, covering a substantial portion of the stream profile, but not readily observable on a 10 m DEM scale.

The high-quality 1 m DEMs, with a vertical resolution of centimeters to decimeters, were acquired by the National Center for Airborne Laser Mapping (NCALM Data Distribution Center, http://calm.geo.berkeley.edu/ncalm/ddc .html). These DEMs were generated using airborne laser imaging detection and ranging data collected in September 2009 during low-flow conditions. The stream network created from LIDAR-derived DEMs agrees with field observations of channels exhibiting sediment transport by fluvial processes. The presence and location of first- and second-order stream basins observed on 1 m DEMs agree with field reconnaissance in both basins. In the Standley Creek basin, stream crossings along the extensive road network were previously mapped during a road-erosion assessment (Pacific Watershed Associates, 2007). Field reconnaissance, stream-crossing data, and the extent of U.S. Geological Survey (1969b) mapped blue-line streams helped define the headwater locations of subtributary streams.

Employing a minimum contributing drainage area of 25×10^3 m^2 to define stream channel initiation provided the best match to the fluvial network documented in the field and on existing U.S. Geological Survey maps. The resulting stream network demonstrates a similar drainage pattern between Standley and Bear Pen Creeks (Fig. 5; Table 1). Stream length differs between the two basins, but the drainage density is similar (Table 1).

The minimum drainage area defining a stream channel (25×10^3 m^2) is much smaller than the widely documented values for the break between colluvial and fluvial processes (10^5–10^6 m^2) (e.g., Dietrich et al., 1993; Montgomery and Foufoula-Georgiou, 1993), but within range of the break observed in other northern California streams (10^4–10^5 m^2) (Snyder et al., 2000). Although fluvial processes dominate downstream of the 25×10^3 m^2 drainage area in South Fork Eel tributaries, streamside landslides still affect these tributaries, which largely flow within inner gorge slopes underlain by potentially unstable Franciscan Assemblage sandstone and shale.

Stream Profile Extraction

Longitudinal profiles were extracted utilizing the stream profiler tool for ArcGIS and MATLAB (http://geomorphtools.org/). Stream channels were sampled at a 0.5 m vertical interval and a 10 m smoothing window was applied using the built-in smoothing algorithm in the stream profiler tool. Smoothed profiles are more representative of the true channel bottom observed in the field because the raw LIDAR elevation data include numerous small pits and features that may represent large woody debris in channels.

Our approach was to generate longitudinal profiles for streams with minimum flow accumulations of 50×10^3 m^2 at their outlets, twice the drainage area at which a channel is well defined (Table 1). The selected stream data set includes all major tributaries and U.S. Geological Survey (1969b) identified blue-line streams on the 7.5 min quadrangles, but reduced the number of first-order basins for analysis. Any stream diverted from its natural channel due to roads or relict logging trails was eliminated from analysis. Streams were selected at their outlet, and followed upstream along the path of the highest order (Strahler, 1952; Fig. 5). At tributary junctions where streams of equal order confluenced, the stream path with the greatest contributing drainage area was followed.

Following the generation of LIDAR-derived profiles, a sampling of streams was checked in the field using a Suunto clinometer to verify that stream slopes on longitudinal profiles agreed with field observations. This method of gradient comparison utilized compact equipment in rough terrain, could be conducted by a single person, and was accurate enough to verify LIDAR-derived profiles.

Identification of Knickpoints and Knickzones

The most thorough method of knickpoint identification was detailed individual-analysis of stream longitudinal profiles. Therefore, major knickpoints were distinguished from inspection of the longitudinal profiles from outlet to headwaters. Major knickpoints separate concave-upward segments of stream channel (Fig. 3).

In addition to inspection on longitudinal profiles, major knickpoint locations along third- to fifth-order streams, tributary to the main stem channels, were analyzed for breaks in the slope-area scaling relation above and below major knickpoints. On log-log plots, clear breaks occur in the slope-area relation at major knickpoint locations. We used the slope-area approach to verify major knickpoints not only because it was more quantitatively rigorous than visual inspection, but also because the slope-area approach enabled subsequent analysis for downstream profile projection from knickpoints (described in the following).

Minor knickpoints, in contrast, locally occasion a steeper pitch of stream channel but do not form a boundary between two reaches each having a distinct concave-upward profile. Rather,
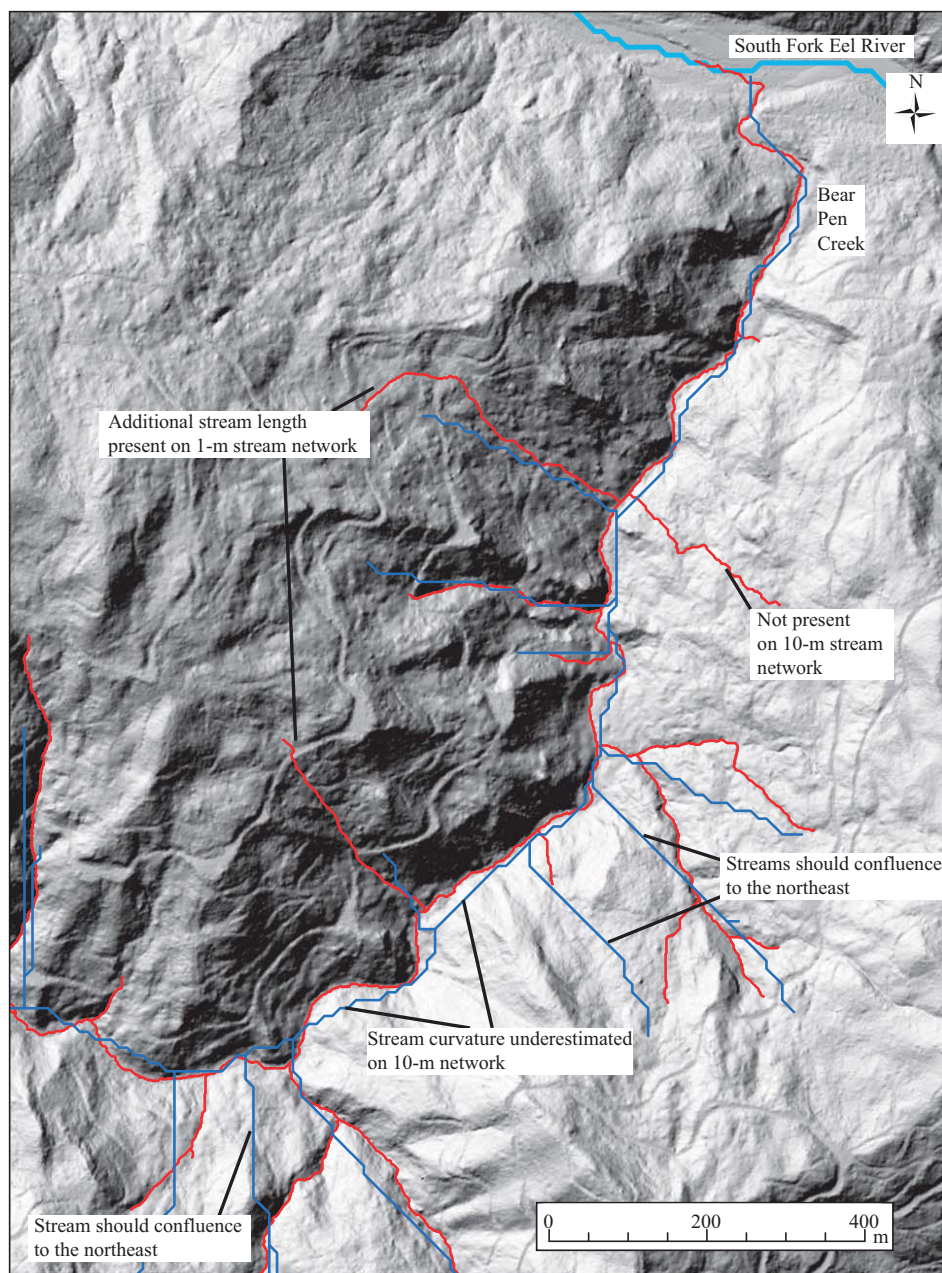
Figure 4. An example of the difference between stream networks generated from 1 m digital elevation models (DEMs) (red) and 10 m DEMs (blue), Bear Pen Creek basin. Stream layers are shown on top of the LIDAR (light detection and ranging) generated hillshade. Note the additional first-order streams present on the stream network generated from the 1 m LIDAR. Two examples of incorrect stream paths on the 10 m DEM are also highlighted. For location references, see Figure 1.

the general concave-upward trend of the longitudinal profile can be projected through minor knickpoints (Fig. 3). Many minor knickpoints occur at erosion-resistant sandstones; this was confirmed easily in the field because they form small waterfalls or cascades.

Major knickzones are more difficult to identify in the field because they extend over long reaches of steeper gradients, across various siltstone and sandstone units, and over a large portion of total stream length and elevation change. Localized field surveys of stream gradient above, throughout, and below major knickzones verified major knickzones identified on longitudinal profiles. Major knickzones are the focus of this study.

RESULTS

Character of the Knickpoint: Steep Face versus Head of Steep Reach

In Standley Creek and Bear Pen Creeks, the knickpoints do not maintain a steep face consisting of a resistant caprock and a less resistant subcaprock, as described by Haviv et al. (2010). Rather, the knickpoints are manifest as the upstream end of a steep reach, the knickzone. The lack of a caprock-subcaprock character to knickpoints in Standley and Bear Pen Creeks is a response to the underlying geology; these two basins are underlain by Franciscan Assemblage sandstones and shales. The sedimentary beds are faulted and tilted. Although the sandstone is the more resistant unit and in the field can form channels with bedrock-lined walls, the sandstone does not form resistant ledges and waterfalls, as is evident in horizontally stratified, little deformed sedimentary units with beds of varying resistance (e.g., Berlin and Anderson, 2007). There are no vertical joints, as described by Lamb and Dietrich (2009) for waterfall-associated knickpoints in volcanic rock, that would promote seepage and vertical calving below knickpoint faces. Sandstone that crops out in channel bottoms in Standley and Bear Pen Creeks accounts for a few of the minor knickpoints where more resistant sandstone may occasion 1-m-high waterfalls. However, comparing field-work observations to LIDAR-derived longitudinal profiles reveals that none of the major knickpoints are at sandstone-shale contacts. Therefore, rather than knickpoint propagation occurring with the headward retreat of a vertical waterfall, knickpoint propagation in Standley and Bear Pen Creeks occurs during incision of a downstream oversteepened reach, the knickzone.

Selected Longitudinal Profiles

The longitudinal profile of the South Fork Eel River from LIDAR-derived DEMs (Figs. 6A, 6B) confirms the presence of a prominent knickzone in the upper profile and also shows two minor knickpoints. The major knickpoint is 150 km above the mouth of the South Fork Eel River and has a total elevation change of ~125 m; the associated knickzone has a reach length of 14.9 km (Table 2), which constitutes 8.3% of the total channel length (Fig. 6A).

In Bear Pen and Standley Creeks, the most notable knickzones occur in the lower profile of the fifth-order main stem streams (Figs. 6C–6F) and extend 3.6 and 3.2 km above the outlet of each channel, respectively (Table 2). Total elevation change within these knickzones is of
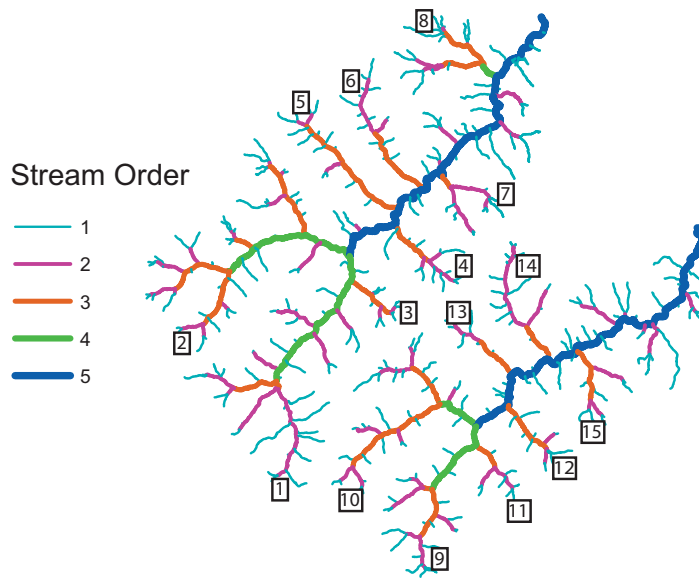
Figure 5. Stream network created using tools for ESRI geographic information systems (GIS), using a minimum contributing drainage area of 25×10^3 m^2 to define stream headwaters. Stream order was defined using GIS tools employing the Strahler (1952) method of channel ordering. Both basins include a main stem, fifth-order channel, and a prominent fourth-order north-fork channel. Numbered channels correspond to third- to fifth-order channels for which slope-area analysis was performed (see Fig. 11).

TABLE 1. TOTAL STREAM LENGTH AND LENGTH OF STREAM ANALYZED WITHIN THE STUDY AREA

	Standley Creek	Bear Pen Creek
Total stream length	75,784 m	52,057 m
Total stream density	4.0 km/km^2	4.0 km/km^2
Analyzed stream length	64 streams, 160–9350 m long	39 streams, 255–8400 m long
Analyzed stream density	2.8 km/km^2	2.7 km/km^2

similar magnitude with a total elevation change of ~85 m in Bear Pen Creek and ~65 m in Standley Creek (Table 2). Above the major knickzone, Bear Pen Creek exhibits a more typical, relatively smooth concave-upward appearance (Fig. 6C), similar to the South Fork Eel River. Standley Creek, in contrast, has two major knickzones above the farthest-downstream knickzone that is correlative to the one knickzone in Bear Pen Creek. These three knickzones in Standley Creek (Fig. 6E) become progressively shorter as distance from the Standley Creek outlet increases. In the main stem channels of both tributaries, several minor knickpoints occur both within and separate from the major knickzones.

More than 800 knickpoints were identified on 103 profiled streams within the study area, including 62 major knickpoints and associated knickzones in the Standley Creek basin and 45 major knickpoints and associated knickzones in the Bear Pen Creek basin. Of the 103 streams analyzed, 22 streams are third- to fifth-order streams and the remaining 81 are first- and second-order streams (Fig. 5). Selected profiles from lower order streams within the study (Figs. 7A, 7C) exemplify that hanging valleys with typical concave-upward profiles above major knickpoints are characteristic of third- and fourth-order subtributary channels. Localized increases in hillslope gradients are also common along knickzones (steep reaches, not waterfalls), suggesting that the hillslopes are not at equilibrium with current stream base level (Figs. 7C, 7E). First- and second-order tributaries tend to have less defined basins and overall straighter profiles than the higher order streams, perhaps due to a lack of stream power, thus minimizing topographic differences above and below major knickpoints (Figs. 7B, 7E).

Knickpoints and Knickzones: Frequency and Distribution

Knickpoint frequency, which is the number of knickpoints per stream length, and knickzone density, which is the percentage of knickzone reach length to total given stream length (Hayakawa and Oguchi, 2006), are similar between the two tributary basins. Major knickzone density is 25% in Standley Creek and 22% in Bear Pen Creek, which represents the portion of the drainage network most actively incising (Fig. 8). Knickpoint frequency for major knickpoints is 1.17 km^{-1} and 1.27 km^{-1} within the Standley Creek and Bear Pen Creek basins, respectively. Major knickpoint frequency remains consistent across stream orders, with the exception of fourth-order streams (Table 3). Knickpoints are less frequent on streams of sequentially higher order, and major knickpoint frequency is greatest on second-order streams (Table 3).

When all knickpoints are considered (both major and minor), there is not a strong relation with elevation or drainage area; however, when considering just major knickpoints along third-, fourth-, and fifth-order streams, there are elevation groupings of these major knickpoints (Fig. 9). Minor knickpoints, in contrast, are widely distributed throughout all elevations.

The grouping of major knickpoints at specific elevation levels suggests that genetically related knickpoints "progress with constant vertical velocity" (Niemann et al., 2001, p. 1331). Niemann et al. (2001) pointed out that such elevation grouping of knickpoints requires conditions where there is spatial homogeneity in erodability and uplift rate. These conditions are met in these two tributary basins because regional uplift rates are the same within contiguous basins of small cumulative drainage area (32 km^2), while at the same time the thin-bedded (millimeter to meter scale) Franciscan Assemblage sandstone and shale are, from an erosion standpoint, homogeneous in their heterogeneity over a 32 km^2 area. Although the region is tectonically active, there is no evidence indicating that the Piercy fault (Fig. 1), the closest fault to the study area, has been active during the Holocene.

Terraces

Fluvial strath terraces, identified from 1 m DEMs and field work, occur along the South Fork Eel River, Standley Creek, and Bear Pen Creek (Fig. 10). Tributary terrace elevations (along Standley Creek and Bear Pen Creek) are mean elevations from the 1 m DEMs (Fig. 10), and denote the elevation of the alluvial surface that defines the terrace tread. Alluvial cover on top of tributary strath terraces along Standley and Bear Pen Creeks is thin, ~1 m. Because alluvial cover is so thin along Standley and Bear Pen Creek terraces, we consider the terrace elevation and the elevation of the strath underlying the terrace to be the same.

A

B

C

D

E

F
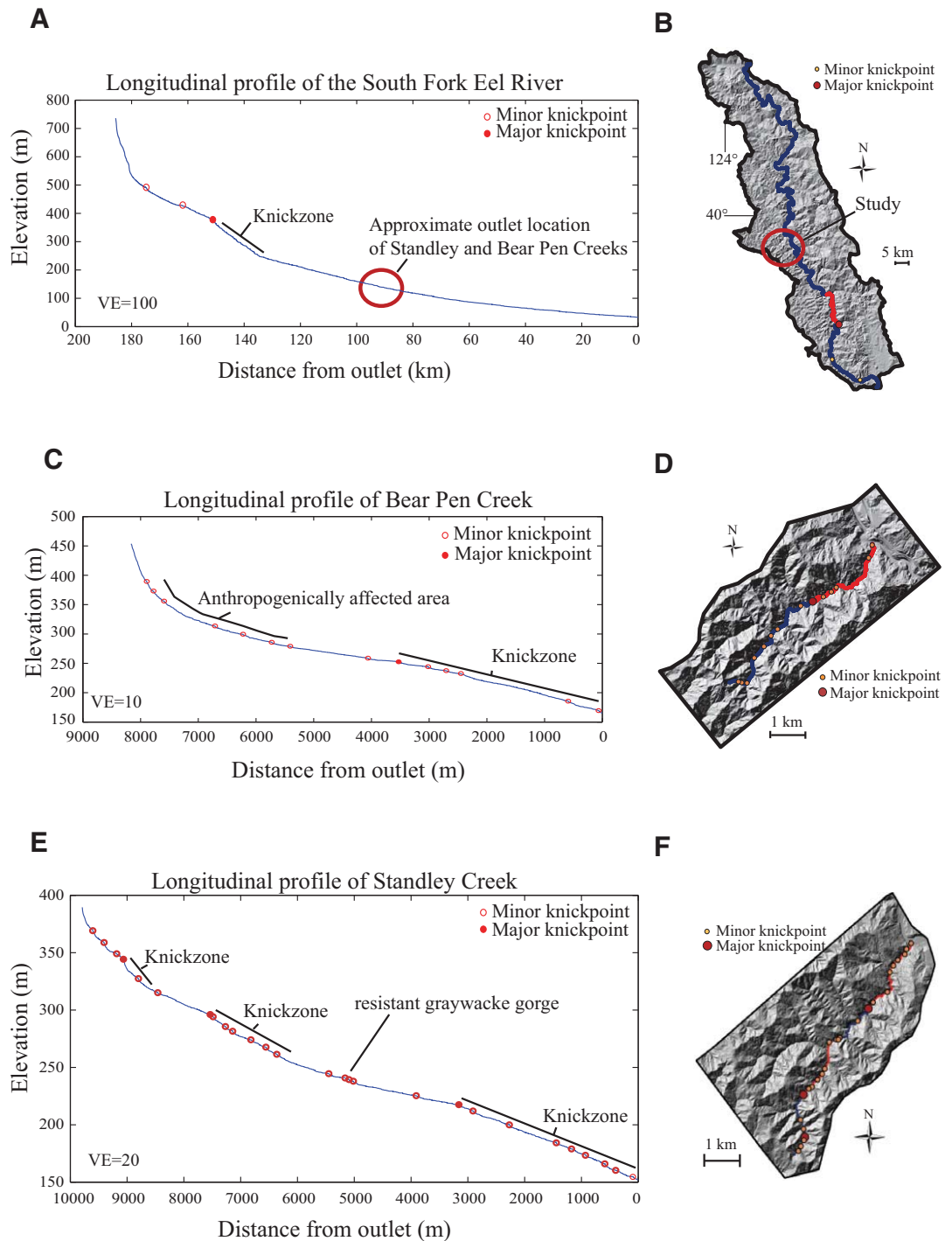
Figure 6. (A) Longitudinal profile of the South Fork Eel River (VE—vertical exaggeration). (C) Longitudinal profile of Bear Pen Creek. (E) Longitudinal profile of Standley Creek. (B, D, F) Major and minor knickpoints, and extent of the downstream major knickzones (channel delineated in red) displayed on hillshades of each drainage basin. On the Standley Creek profile (E), the 3 minor knickpoints clustered around 5200 m above the outlet flow through a resistant graywacke gorge. Bear Pen Creek (D) is the southern basin, and Standley Creek is the northern basin (F) within the study area.

For South Fork Eel River terraces proximal to the mouths of Standley and Bear Pen Creeks, the alluvial cover above the strath surface is multiple meters in thickness and the elevation of the strath is significantly lower than the elevation of the terrace. For the South Fork Eel River terrace near the Standley Creek confluence (the terrace with an elevation of 227 m, Fig. 10), the thickness of alluvium overlying the bedrock strath is ~14 m. On another South Fork Eel River terrace near the town of Leggett (Fig. 1), the thickness of alluvium overlying the bedrock strath is 11 m. Based on these measurements, we represent the bedrock strath as 10–15 m below the elevation of the terrace surface (Fig. 10). If Standley and Bear Pen Creeks were graded to a previous base level associated with these South Fork Eel River terraces, it is the elevation of the bedrock strath to which they would grade.

TABLE 2. ATTRIBUTES OF SOUTH FORK EEL RIVER KNICKZONE AND FIFTH-ORDER STREAM KNICKZONES

Drainage basin	Knickzone elevation change (m)	Knickzone length (km)
South Fork Eel River	125	14.9
Bear Pen Creek	85	3.6
Standley Creek	65	3.2

Knickpoint and knickzones in the South Fork Eel River, California
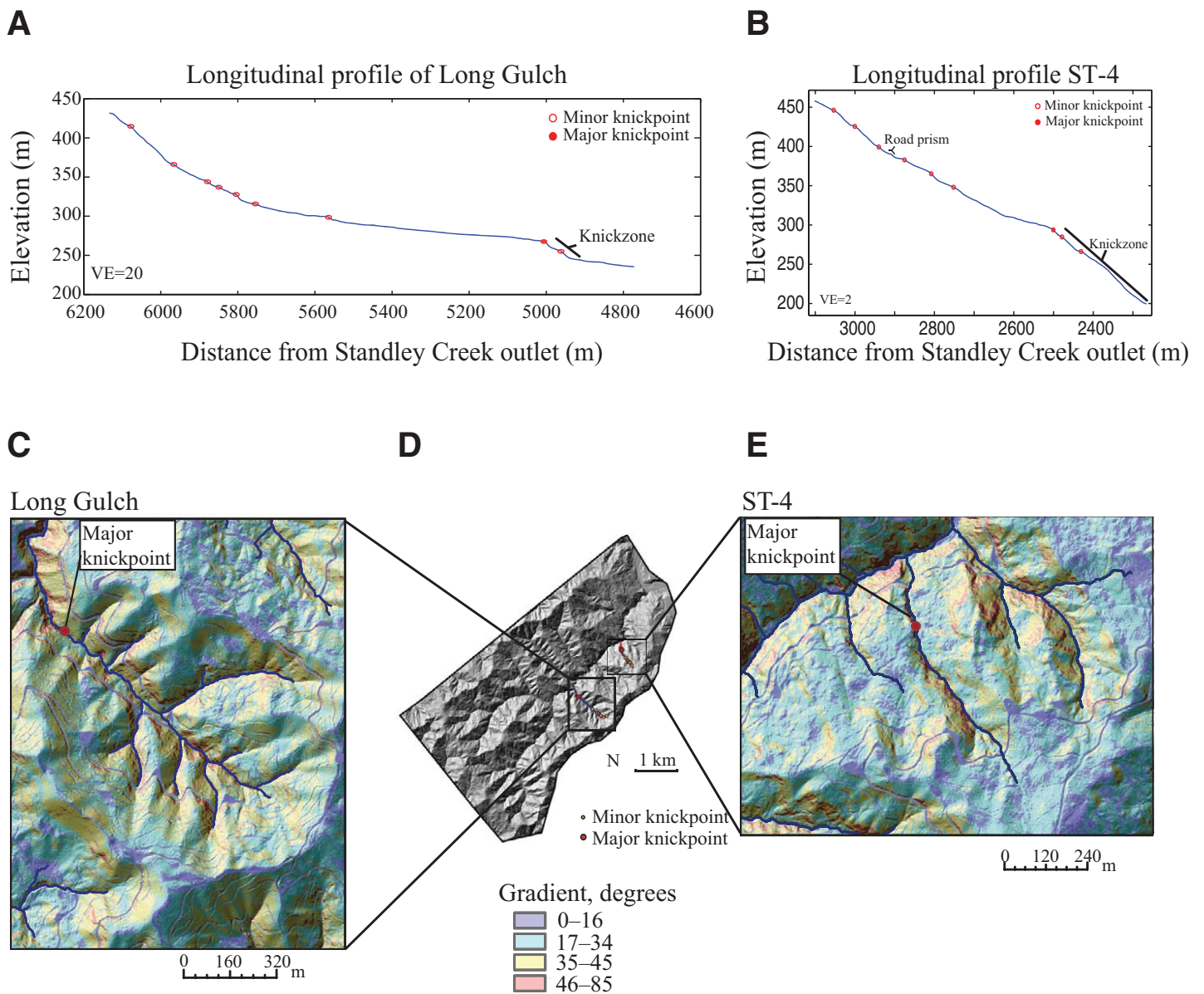
Figure 7. (A) Longitudinal profile of third-order stream Long Gulch, Standley Creek basin. (B) First-order stream Standley Creek tributary 4 (ST-4), Standley Creek basin. Each stream displays a prominent knickpoint and knickzone in the lower portion of the longitudinal profile, just upstream from the confluence with Standley Creek. The Long Gulch confluence with Standley Creek is between the lower and middle knickzones. (C) A large hanging valley is present above the Long Gulch knickzone, whereas steep gradients characterize the streamside slopes through the knickzone. ST-4 is located in the lower portion of the Standley Creek watershed, and confluences with the main stem within the lower knickzone along Standley Creek. (D) Standley Creek basin. (E) Like many low-order streams in the study area, ST-4 has little valley definition and does not display a very concave stream above the major knickpoint (B), likely due to lack of stream power. Note that one of the minor knickpoints was eliminated because the gradient inflection is due to a road prism (B). (A road prism is the area containing the road surface, including cut and fill slope portions.) For location reference, see Figures 1 and 2.

Slope-Area Trends and Major Knickpoints

Along third- to fifth-order streams tributary to the main stem channels, a factor of 2–3 increase in slope is common at major knickpoints (Fig. 11). For this analysis (modified from methods developed by Wobus et al., 2006), slope and drainage area data for each stream were grouped by drainage area into 200 log-bins per decade of log space. Slope-area trends were then defined above and below major knickpoints.

We performed linear regressions on log-transformed slope-area data above and below drainage areas corresponding to major knickpoints identified along longitudinal profiles (Fig. 11).

When more than one major knickpoint is present on a tributary, there is often not enough of a gap in drainage area to perform regressions on each segment. In these cases, regressions may be omitted or grouped (Fig. 11). We have shown these regressions (Fig. 11) because they display the differences in the slope-area scaling relation for reaches separated by major knickpoints.
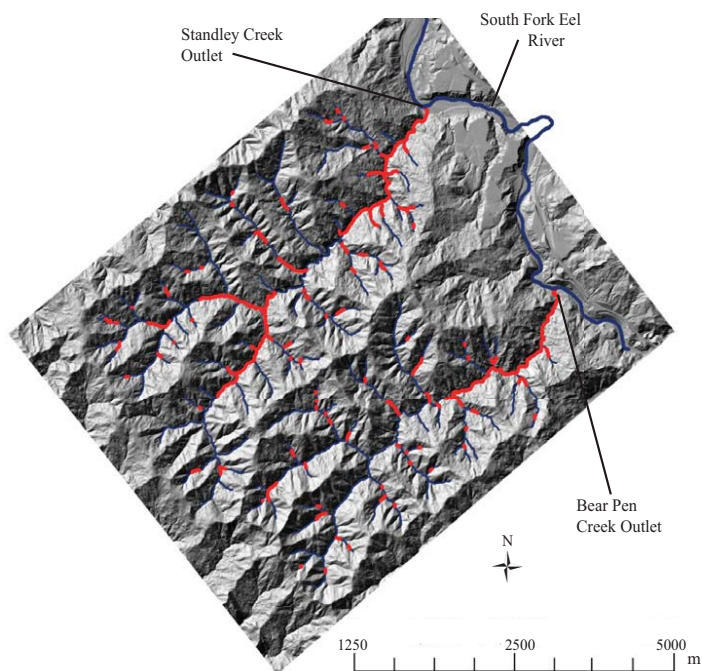
Figure 8. Major knickzone density in the Standley and Bear Pen Creek drainage basins. Knickzones are delineated as red channel reaches. The channel network as a whole (blue-line streams and knickzones) represents all streams selected for profile analysis. For location reference, see Figure 2.

Stream concavities (slope of the slope-area regression in Fig. 11) vary above and below major knickpoints; and in many cases, the concavity and steepness increase downstream from major knickpoints (Fig. 11). For reaches farthest upstream, above any major knickpoint, the concavities typically trend around 0.6–0.8 (Fig. 11). From these observations we infer that, although the reference concavity for slope-area scaling models for streams undergoing steady uplift is generally 0.45 (Kirby and Whipple, 2001), a reference concavity of 0.45 is too small for the South Fork Eel River tributaries.

Projections of Paleolongitudinal Profiles

Linear regressions on log-transformed slope-area data above major knickpoints are used as a basis for projecting relict, or paleolongitudinal profiles. Relict profiles for third- and fourth-order subtributaries were projected based on the linear regressions of slope-area data above major knickpoints (Fig. 11; see Appendix 1). These projections were used to plot the elevations of relict tributary outlets (Fig. 10). However, in using this approach, where steepness and concavity covary, there are large fluctuations in elevation associated with tiny changes

in concavity, thus resulting in an unrealistically large range of projections.

To better represent the uncertainty associated with paleolongitudinal profile projections, we use a fixed reference concavity of 0.70, which is the median concavity for channel regressions from stream headwaters to the most upstream major knickpoint (i.e., Fig. 11). Normalized steepness indices (Whipple and Tucker, 1999), derived with the reference concavity, were used to calculate channel slopes in paleolongitudinal profiles of the main stem channels (see Appendix 1). In addition, this projection method was used as

a second method of projecting relict tributary outlets (Fig. 10).

All paleolongitudinal profiles were projected using a second-order Taylor series approximation to predict the channel elevation at higher drainage areas based on the channel elevation at the previous drainage area. The paleolongitudinal profiles for the main stem Standley and Bear Pen tributaries, shown as black dashed lines in Figure 10, extend down-profile from the major knickpoints and gradually flatten toward the outlet as drainage area increases. The green dashed lines above and below each paleolongitudinal profile represent the error associated with the normalized steepness index (k_{sn}) fit to the model (see Appendix 1 for a more thorough description of method and error estimation).

Only one paleolongitudinal profile can be projected along the main stem of Bear Pen Creek because there is only one major knickzone, whereas three paleolongitudinal profiles are projected for Standley Creek because of the presence of three major knickzones (Fig. 10). Two observations are apparent from paleolongitudinal profile projections.

(1) If stream reaches above major knickzones in tributaries to Standley Creek are projected onto the longitudinal axis of Standley Creek (projected tributary outlets, Fig. 10), the outlet elevations where these projected tributaries intersect the valley axis are coincident with the zone of possible paleolongitudinal profiles associated with the second major knickpoint in Standley Creek. In addition, the elevation of terraces, with one exception, along Standley Creek aligns with the same zone of paleolongitudinal profiles (Fig. 10).

(2) The projected tributary outlets in Bear Pen Creek align onto an upper paleolongitudinal profile, but in this case the upper paleolongitudinal profile is solely defined by these projected tributary outlets. In contrast, the lower paleolongitudinal profile in Bear Pen Creek (Fig. 10) extends from the one major knickzone.

TABLE 3. CLASSIFICATION OF KNICKPOINT FREQUENCY AT EACH STREAM ORDER
FOR THE STANDLEY CREEK AND BEAR PEN CREEK DRAINAGE BASINS

Drainage basin	Stream order	Stream length (km)	Major KPs*	Minor KPs*	Total KPs*	Major KP* frequency (km⁻¹)	Minor KP* frequency (km⁻¹)	Total KP* frequency (km⁻¹)
Standley	1	19.37	29	258	287	1.50	13.31	14.81
Bear Pen	1	10.72	16	120	136	1.49	11.20	12.69
Standley	2	13.24	21	143	164	1.59	10.80	12.39
Bear Pen	2	10.13	20	99	119	1.97	9.77	11.74
Standley	3	10.54	9	47	56	0.85	4.46	5.31
Bear Pen	3	6.80	8	33	41	1.18	4.85	6.03
Standley	4	4.44	3	11	14	0.67	2.47	3.14
Bear Pen	4	1.96	0	5	5	0	2.55	2.55
Standley	5	5.54	1	11	12	0.18	1.98	2.16
Bear Pen	5	5.78	1	7	8	0.173	1.21	1.38

*KP—knickpoint.
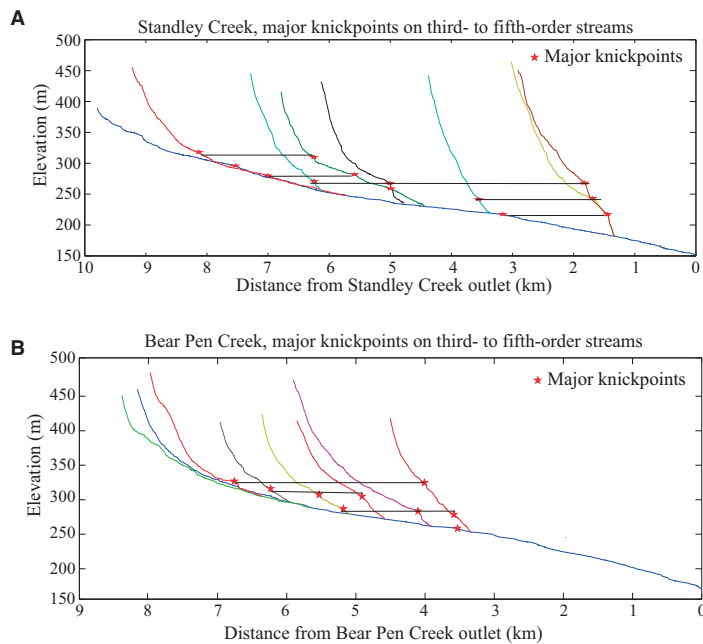
Figure 9. Composite longitudinal profiles of main channel tributaries and subtributaries, third- to fifth-order streams, showing major knickpoints. Tie lines indicate elevation groupings of major knickpoints on different tributaries. (A) Standley Creek watershed. (B) Bear Pen Creek watershed.

DISCUSSION

Trends in Knickzone Length and Gradient with Drainage Area

Knickzone length decreases and knickzone gradient increases at higher elevations (Figs. 12A and 12B, respectively), indicating that knickzones become shorter and steeper as they propagate up a basin. This is not unexpected because stream gradient also increases as drainage area decreases, and the propagation of knickzones along stream reaches with increasing background gradients ultimately results in decreasing overall length of knickzones.

An ultimate outcome of knickzone gradient increasing at higher elevations is that eventually upstream-propagating knickzones become indistinguishable from background steep channel gradients. Seidl and Dietrich (1992) found that an upstream-propagating wave of incision may terminate at steep channel reaches rather than continuing to propagate to stream headwaters.

Elevation Groupings of Major Knickpoints

Major knickpoints group by elevation. Because higher order tributaries generally have greater contributing drainage area, knickpoints propagate more quickly along the higher order main stem channel and more slowly in lower order tributaries. By this reasoning, knickpoints occur at similar elevations (Wobus et al., 2006; Niemann et al., 2001). Harkins et al. (2010) also found that knickpoint distributions grouped at similar elevations regardless of drainage area. Elevation groupings of major knickpoints are apparent when eliminating first- and second-order channels (Fig. 9). We eliminate these channels because they are topographically poorly defined and major knickpoints are difficult to distinguish on first- and second-order channels.

The most striking aspect of the elevation grouping of major knickpoints in the two study tributaries (Fig. 9) is that the major knickpoints in tributary channels, without exception, group above the elevation of the farthest downstream prominent knickpoint on the main stem channel. Major knickpoints in tributaries to Standley Creek roughly correlate with the second upstream major knickpoint along Standley Creek (Fig. 9A). In Bear Pen Creek, the majority of knickzones occur along tributaries that join the main stem above the major knickpoint on Bear Pen Creek (Fig. 9B). Although there are no major knickpoints along the upper trunk stream of Bear Pen Creek with which to correlate major tributary knickpoints, there are several minor knickpoints located in the upper portion of the Bear Pen Creek profile (Fig. 6). Previous major knickpoints could now be represented as only discrete smaller knickpoints within the upper steep reaches of Bear Pen Creek.

Generation of Major Knickzones: Internal or External Control?

The South Fork Eel River knickzone and many of the knickzones within the two study tributaries occur at or between large tributary junctions, and we address the question of the extent to which major knickzone distribution is influenced by sudden changes in drainage area. Knickzones may initiate on tributary channels to keep pace with the relatively quicker incision along the main stem channel (Seidl and Dietrich, 1992). Knickzone propagation may also stall due to a channel's inability to adjust to a large change in drainage area at tributary junctions (Crosby and Whipple, 2006), or if knickzone slopes increase to the point that channel erosion from sediment impact is infrequent and ineffective (Crosby et al., 2005). These processes affecting knickpoint distribution are internal controls, as opposed to episodic base-level fall, which is an external control.

Not all major knickzones in the two tributary basins are found near subtributary junctions, and stalled knickzones at subtributary junctions do not necessarily eliminate an external control on knickpoint initiation. Transient knickpoints will propagate more slowly along subtributaries than along on the main stem due to decreased drainage area, thus causing an increased occurrence of transient knickzones near tributary junctions.

The lowermost knickzones on both Standley and Bear Pen Creeks are of similar elevation, magnitude, and length (Table 2), from which we infer that the associated knickpoints were triggered by the same base-level lowering event. The elevation change throughout the major knickzone on the South Fork Eel River is also of similar magnitude (Table 2), and passage of this propagating knickzone is likely correlated with formation of the lowermost knickzone in both Standley and Bear Pen Creeks (Figs. 6 and 8).

We infer that an external control exerted by a period of increased incision along the South Fork Eel River is responsible for knickpoint initiation within these two drainage basins. Within the subtributary basins, the presence of hanging valleys above major knickpoints, as well as oversteepened sideslopes along knickzone reaches, (e.g., Long Gulch, Fig. 7) is consistent with the inference that upper basin knickzones represent pulses of incision initiated by base-level fall.
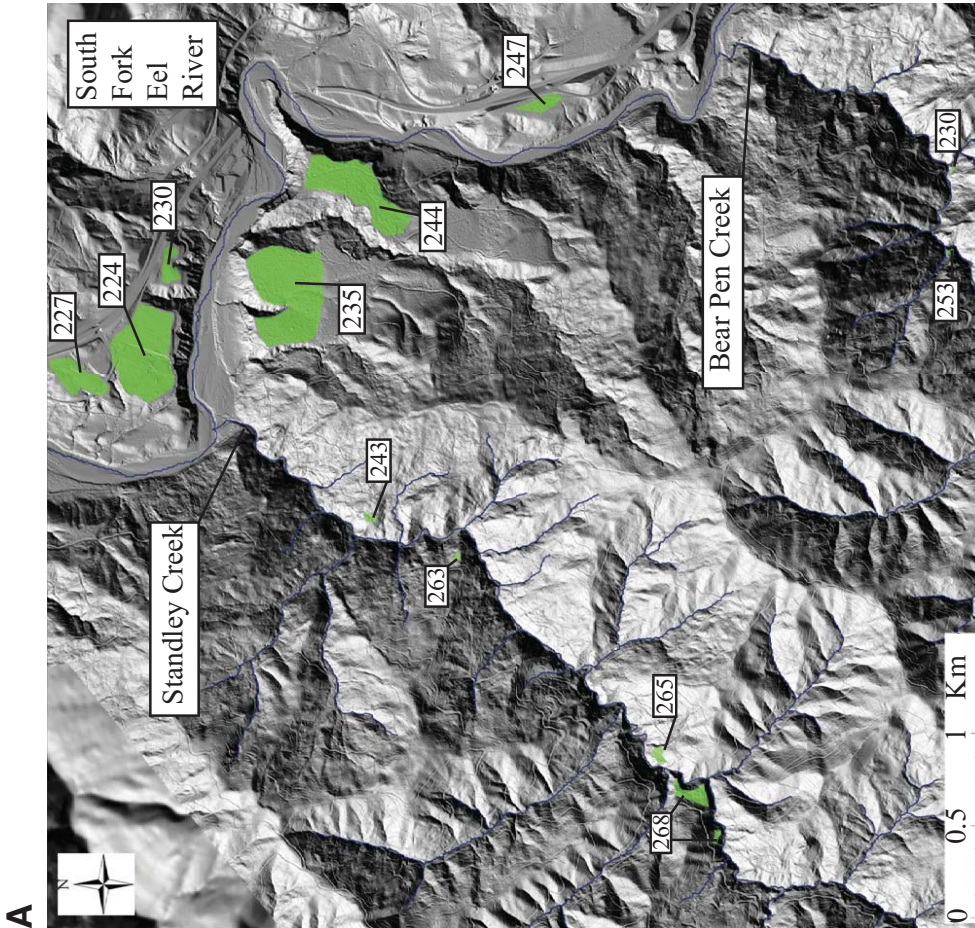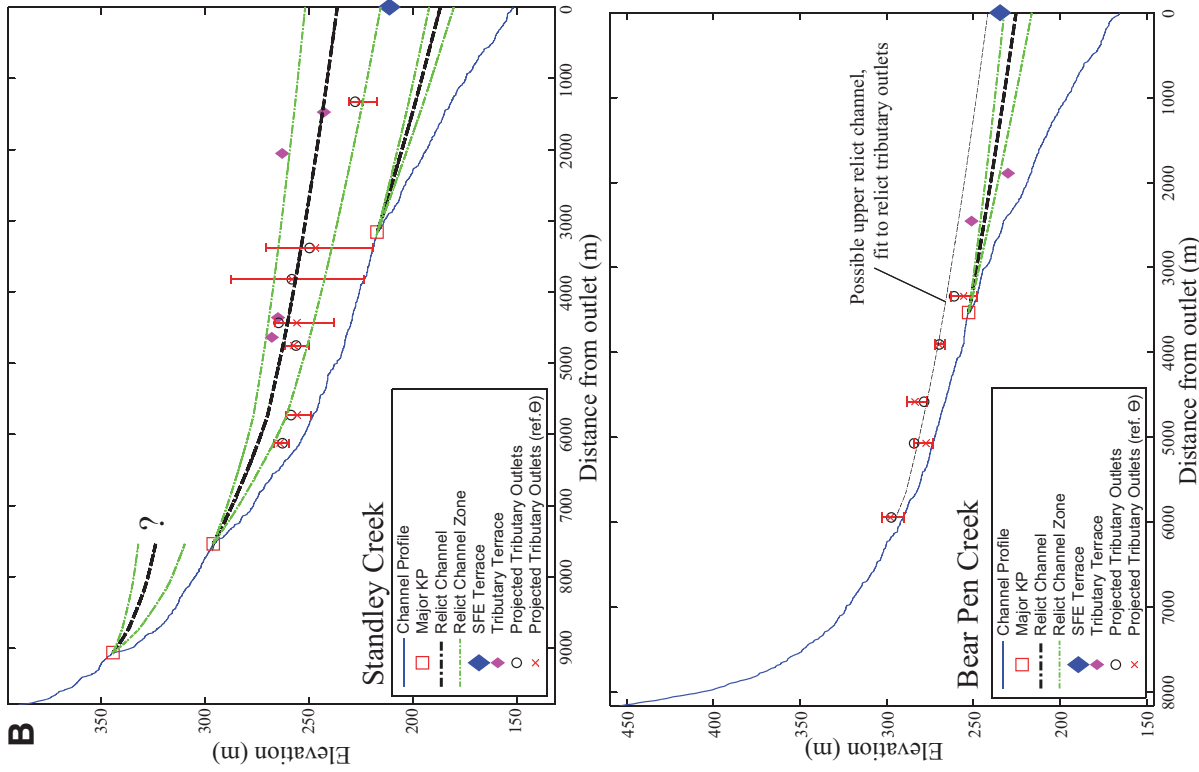
Foster and Kelsey

Figure 10. (A) Hillshade depicting terraces along the South Fork Eel River, and Standley and Bear Pen Creeks. Terrace surfaces are highlighted in green. Numbers represent mean terrace elevation in meters. (B) Modern and projected pre-incision longitudinal profiles (relict channels; for detailed discussion of projection methods, see Appendix 1). Relict channels were projected using method 2. Projected tributary outlets represent the elevation of pre-incision tributary outlets, based on projection of their paleolongitudinal profiles using method 1. Projected tributary outlets (ref Θ) were calculated using method 2. Error bars represent the possible range in k_{sn} (k_{sn}—normalized steepness index) values in method 2. The upper relict channel (thinner black-dashed line) along Bear Pen Creek is not tied to a major knickpoint, but rather to the elevations of the relict tributary outlets. The closest South Fork Eel River (SFE) bedrock-strath elevation is plotted at the outlet of Standley and Bear Pen Creeks (blue diamonds). KP—knickpoint. For location reference, see Figure 2.

Knickpoint and knickzones in the South Fork Eel River, California
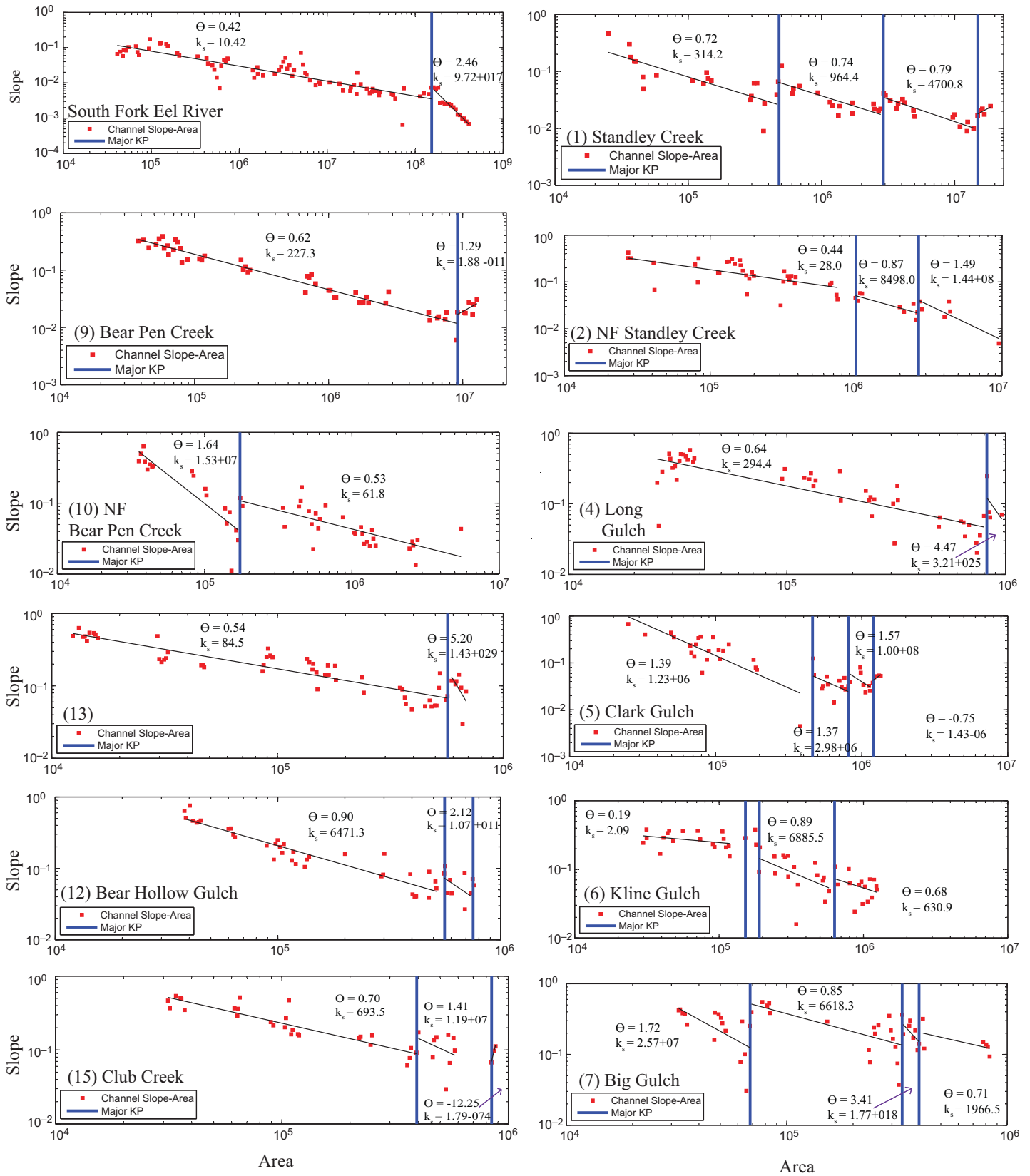
Figure 11. Slope-area fits for South Fork Eel River, Bear Pen and Standley Creeks, and selected third- and fourth-order subtributaries. Red boxes represent log-bin averages of channel slope. Drainage area was divided into 200 possible log-bins per log decade; however, drainage-area data may not exist for every designated bin. Bold blue lines represent drainage areas at which major knickpoints (KP) occur. Numbers above the legend correspond to the geographic location in Figure 5 (Θ—concavity index; k_s—steepness index).

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A

B
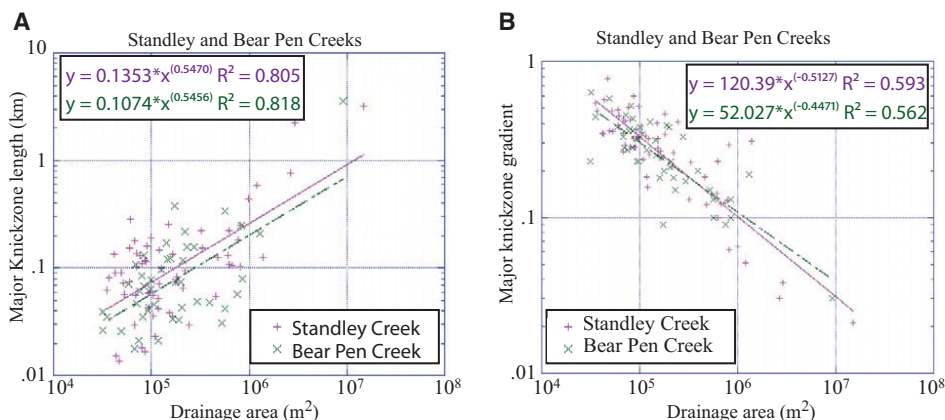
Figure 12. (A) Relation between knickzone length and contributing drainage area at major knickpoint location. (B) Relation between knickzone gradient and contributing drainage area at the major knickpoint.

Major knickpoints within our study area are represented by a distinct break in the slope-area scaling relation, described by Haviv et al. (2010) as slope-break knickpoints. Slope-break knickpoints are generally transient, and represent a prolonged change in forcing (Kirby and Whipple, 2012; Wobus et al., 2006). Minor knickpoints in our study area do not display a break in slope-area scaling, and are thus vertical knickpoints. They are stationary, forming at small areas of resistant graywacke sandstone.

Projection of Tributary Paleolongitudinal Profiles to Terraces on the South Fork Eel River

The lowest major knickpoints in Bear Pen and Standley Creeks are correlative in elevation and distance above their respective creek mouths, and we hypothesized that the projected paleolongitudinal profiles from these two knickpoints would intersect the South Fork Eel River at the elevation of the strath surface of a prominent set of alluvial terraces. However, the elevation of the most likely correlative strath on the South Fork is above paleolongitudinal profile projections from the lowest major knickpoints (Fig. 10). In the case of Standley Creek, the elevation of the most likely correlative strath on the South Fork Eel River is just below the channel projection from the second-highest major knickpoint. In the case of Bear Pen Creek, the projection from the one major knickpoint intersects the South Fork Eel River valley axis below the strath on the South Fork Eel River, whereas the upper relict channel of Bear Pen (fit to tributary outlets) projects barely above the strath on the South Fork Eel River (Fig. 10).

Although the lowest major knickpoint on the two tributaries seemed to be the obvious one

to correlate with the lowest major abandoned strath surface on the South Fork Eel River, they are not correlative because the elevation of the South Fork Eel strath is too high. The next-highest paleolongitudinal profile on the two tributaries is a better fit to the elevated strath on the South Fork Eel (Fig. 10). However, the lack of a clear correlation of either set of paleolongitudinal profiles on the tributaries to the prominent straths on the South Fork is an indication that the projection methods and assumptions in this case are unsuitable for resolving paleochannel elevations to <20 m over projection distances of 6–8 km.

Using the same projection method from the lowest major knickpoint for both Standley and Bear Pen Creeks, the projected elevation difference at the tributary mouths was 25 m, with the upstream Bear Pen tributary mouth being 25 m above the downstream Standley Creek tributary mouth. However, in modern times, the Bear Pen outlet is only 15 m elevation above the Standley Creek outlet. From the difference between modern profiles and modeled paleoprofiles, we infer that slope-area scaling above the lowest major knickpoint is not constant in each of the two tributaries over time (which is an assumption of the modeled projection), even though tributaries are adjusting to the same external base-level fall. A related pertinent observation is that streams in our study area demonstrate a range of concavities (Fig. 11), while Snyder et al. (2000) made the case that concavity remains constant under steady-state conditions. We suggest that the two tributaries have independent, time-varying slope-area scaling because the tributaries respond to multiple instances of base-level fall over time scales of 10^5 to 10^6 yr. Such time-variable slope-area scaling precludes model-

predictable correlation of major knickzones in the two tributaries with respective strath elevations along the downstream trunk stream.

Multiple Events of Base-level Lowering on the South Fork Eel

The two tributaries record multiple events of base-level fall. If all knickpoints in the two tributaries were related to the recent event of base-level drop in the South Fork, then tributary major knickpoints should be concentrated in higher order streams. However, tributary knickpoints in the Standley and Bear Pen drainages are not exclusively concentrated in high-order streams (Fig. 9). The lowest major knickpoint on both Standley and Bear Pen Creeks can be related to the one major knickpoint on the South Fork Eel River, but other major knickpoints and associated terraces on the two tributaries, most of which can be grouped by elevation, must be related to prior events of base-level fall on the main stem. In addition, projection of relict subtributary outlets grade to a base level above the lowest major knickpoint along the main stem channels in each tributary basin (Fig. 10). Observations from the Bear Pen and Standley tributary drainages therefore lead us to infer multiple base-level lowering events on the South Fork Eel River over the same time frame.

The presence of only one major knickzone along the South Fork Eel River is not contradictory to multiple events of base-level fall. The South Fork Eel River knickzone occurs directly above the tributary confluence of Rattlesnake Creek. Therefore, the knickzone occurs just upstream of a significant decrease in drainage area. It is possible that multiple propagating knickpoints in a trunk stream stall, or undergo a drop in celerity, where drainage area becomes too small to produce the stream power necessary to promote channel incision (Crosby and Whipple, 2006). Below the South Fork Eel River knickzone, the trunk stream has the power to adjust to base-level perturbations and reach a new steady-state condition. Above the major knickzone, the headwater trunk stream of the South Fork Eel River does not have the power to propagate the pulse of incision farther upstream. Thus, the one major knickzone on the South Fork Eel River could contain a composite of multiple stalled major knickzones.

We implicate multiple base-level lowering events forced by an external control, which begs the question, what is forcing function? The candidate external controls are climate and tectonics. However, it is not clear from the topographic characteristics of the South Fork Eel River drainage basin which external control is more likely. Timing of base-level lowering

events may implicate one external control over the other. Fuller et al. (2009) suggested, from terrace dates and paleoerosion rates derived from strath sediments along a 5 km reach of the South Fork Eel River near Elder Creek (Fig. 2), that climate changes drive differences in sediment supply that control incision or lateral planation. However, the lack of more comprehensive, basin-wide timing information leaves open the question of the most likely forcing function for multiple base-level lowering events.

CONCLUSION

Standley and Bear Pen Creeks, two drainages of equal size (13–19 km^2) that are tributary to the South Fork Eel River, have multiple major knickpoints and associated knickzones along main stem and tributary channels. Major knickpoints are not the heads of waterfalls, but rather are at the heads of anomalously steep reaches (the knickzones). In general, within each tributary basin, sets of major knickpoints on different subtributary channels group by elevation. Prominent knickpoints on high- and low-order channels, situated at the head of steep knickzones, are equivalent in elevation. Major knickpoints are obvious on depictions of longitudinal profiles constructed from LIDAR-derived 1 m DEMs because they separate two reaches, each with a concave-upward profile. Consistent with this observation, major knickpoints separate reaches of distinctly different slope-area scaling relationships. The distinctive slope-area scaling relation for reaches between stream headwaters and a major knickpoint serves as a basis for evaluating an appropriate reference stream concavity for the two tributaries. The reference stream concavity is employed to project paleolongitudinal profiles outward from major knickpoints.

We conclude, on the basis of projection of paleolongitudinal profiles to downstream valley axes, as well as on the observation of multiple knickpoint and knickzone reaches in the tributaries, that there have been multiple instances of base-level fall on the South Fork Eel River. These instances of base-level fall have resulted in the upstream propagation along tributary channels of knickpoints. In addition, a prominent knickpoint on the South Fork Eel River, 50–60 km upstream of the tributary basins, is not inconsistent with the hypothesis of multiple instances of base-level fall at the tributary mouths.

In summary, the major knickpoints on the tributaries are transient. Sets of major knickpoints group by elevation, and these sets of major knickpoints ultimately owe their origin to base-level fall events on the South Fork Eel

River. A significant aspect of our observations is that, from DEM analysis of these two tributary basins, incision of channels into the South Fork Eel River basin landscape does not occur at a gradual and constant rate. Rather, profiles of the channels preserve an episodicity of incision pulses. The two fundamental external controls on incision are climate and tectonics, but what specific forcing function accounts for the episodicity of incision remains unclear.

APPENDIX 1: METHODS OF PROJECTING PALEOLONGITUDINAL PROFILES

The projection of paleolongitudinal profiles is based on the power-law relation between slope and drainage area (Hack, 1973; Flint, 1974). Drainage area is used as a proxy for discharge (Howard and Kerby, 1983) allowing slope (*S*) and drainage area (*A*) to be related through the steepness index, k_s, and the concavity index (Θ), (e.g., Whipple and Tucker, 1999; Wobus et al., 2006; Snyder et al., 2000), such that

$$S = k_s A^{-\Theta}. \qquad (1)$$

Gradient measurements using unsmoothed elevations across 1 m pixel resolution generate a large amount of noise and scatter. To smooth gradient data, we grouped data into 200 log-bins per log-decade space (method modified from Wobus et al., 2006). Linear regressions were fit on log-transformed data, on user-specified stream reaches. We used the drainage area associated with major knickpoints as bounds for our regression fits, with the exception of reaches between major knickpoints where insufficient drainage area existed to perform a linear regression.

To project paleolongitudinal profiles, we assume that the paleotopography below major knickpoints has the same slope-area scaling relation currently found above major knickpoints. The concavity, Θ, represents the rate of change in channel gradient with respect to drainage area (the second derivative of the longitudinal profile) and the steepness index k_s is related to the y-intercept. Using the corresponding drainage area and distance from the outlet for each pixel, we create a paleolongitudinal profile using this slope-area scaling relation. The elevation at the upstream end of the paleoprofile is anchored at the elevation of the major knickpoint. Elevation at a downstream data point (*x*) is predicted based upon the elevation at the adjacent upstream data point (*x* + *dx*) using a second-order Taylor series approximation, such that:

$$y_{(x)} = y_{(x+dx)} - [S_{(x+dx)} \times dx] + (0.5 \times dx^2 \times dS/dx), \quad (2)$$

where *y* is elevation, *x* is the distance along the stream profile, *dx* is the change in *x* between data points, and *d*S is the change in slope over *dx*.

Paleolongitudinal projections were done in two ways: method 1, using the Θ and k_s values calculated from slope-area regressions, and method 2, using a reference concavity (Θ_{ref}) of 0.70 and normalized steepness indices (k_{sn}). The slope is then calculated using Equation 1 with Θ and k_s (or Θ_{ref} and k_{sn}). Method 1 produces an unrealistically large range of profile projections (i.e., large error bounds) because steepness and concavity are allowed to covary. Therefore, we present tributary outlets calculated using method 1 merely for comparison with method 2. In method 2, the error is derived from the k_{sn} value, as concavity is fixed. We used a MATLAB function to calculate

the standard (std) deviation in the k_{sn} values. We then calculated the high and low possibilities for k_{sn} values (e.g., $k_{sn}hi = k_{sn} + std$). The high and low k_{sn} values are then used to project the range of possible paleolongitudinal profiles, or the range of relict outlet locations (see Fig. 10). In two instances, the lower error bound for the relict tributary outlets was truncated at the current channel elevation, because current topography imposes an additional bound on the range of projected tributary outlet elevations. Large error bars are likely related to a large deviation between actual channel concavity and the reference concavity.

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