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Sediment supply, base level, braiding, and bedrock river terrace formation: Arroyo Seco, California, USA

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ABSTRACT

In many settings, rivers alternate between carving wide valley bottoms (straths) and cutting narrow gorges over time, thereby creating longitudinally continuous paired bedrock strath terraces along valleys. Strath terraces are used ubiquitously in geomorphology and tectonics; however, how and why they form remain poorly understood. Here, we focus on Arroyo Seco in the central California Coast Ranges, where we test hypotheses for strath planation and subsequent strath terrace formation. Several lines of evidence indicate that strath planation is triggered by braiding in bedrock channels. In particular, hydraulic modeling reveals that the width of Arroyo Seco's most recently formed terrace is comparable to the width of currently braided channel reaches. Additionally, a comparison of currently braided reaches to abandoned bedrock meander cutoffs shows that braided channels have valleys that are several times wider than single-thread meandering bedrock channel reaches. Lastly, in locations where the modern channel is currently braided, terraces are poorly preserved, suggesting that evidence for past episodes of braiding, in the form of paired strath terraces, is apparently largely destroyed by subsequent episodes of braiding. Field observations combined with mapping of terrace levels using an objective light detection and ranging (LiDAR)–based terrace identification algorithm reveal that temporal variation in tectonic uplift rate, sea level, and/or alluvial cover along the river cannot explain strath planation and subsequent terrace formation in Arroyo Seco. Rather, our results provide evidence that aggradation and degradation of alluvial sediments downstream of the Reliz Canyon fault result in impulsive base-level forcing of Arroyo Seco's bedrock channel. Strath abandonment and terrace formation apparently occur as incision into downstream alluvial sediments propagates upstream into bedrock. Braiding and planation of straths, in contrast, occur during intervals of low vertical incision rate associated with downstream aggradation or immediately following pulses of vertical lowering triggered by downstream incision of alluvial sediments.

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INTRODUCTION AND MOTIVATION

Bedrock strath terraces, abandoned river-worn bedrock surfaces blanketed in gravel, are commonly used to reconstruct incising river paleoprofiles. Consequently, longitudinally continuous strath terraces provide essential constraints on rock deformation (e.g., Lavé and Avouac, 2000; Molnar et al., 1994; Pazzaglia and Gardner, 1994; Rockwell et al., 1984; Shyu et al., 2006; Simoes et al., 2007), spatial patterns of bedrock incision (e.g., Lavé and Avouac, 2001; Pazzaglia and Brandon, 2001; Personius, 1995), and changes in river longitudinal profile slope with time (e.g., Merritts et al., 1994). However, the mechanisms by which bedrock terraces form are not well understood (e.g., Montgomery, 2004). Explanations for strath planation and subsequent strath terrace formation appeal to both climate, via its control on sediment load relative to river discharge (e.g., Bull, 1990; Molnar et al., 1994), and tectonics (e.g., Chen et al., 2002; Cheng et al., 2002; Yanites et al., 2010) and sea-level change (e.g., Castillo et al., 2013; Pazzaglia and Gardner, 1993), via their control on river base level. Bedrock terraces are therefore interpreted as both paleoclimatic and paleotectonic proxies in different settings.

CONCEPTUAL MODELS FOR STRATH TERRACE FORMATION

G.K. Gilbert, W.M. Davis, and J.H. Mackin argued that lateral planation of wide bedrock valley bottoms, known as straths (Bucher, 1932), is tied to the balance between sediment supply and transport capacity in channels (Davis, 1909; Gilbert, 1877; Mackin, 1948). Specifically, all three authors reasoned that when the coarse sediment load supplied from upstream is balanced by the transport capacity downstream (i.e., a graded condition is achieved), coarse sediment deposition in a river would armor the bed, suppress vertical incision, and therefore enhance lateral channel erosion relative to vertical channel incision. Although Davis viewed strath planation as a stage in the "Geographic Cycle" (Davis, 1909), whereas Gilbert and Mackin viewed strath formation as a reflection of the tendency for streams to evolve to balance the load supplied from upstream (Gilbert, 1877; Mackin, 1948), both Davis and Gilbert argued that straths were incised and abandoned (and bedrock strath terraces thereby created) from downstream river base-level drop, presumably because steepening of the channel would result in excess transport capacity and vertical incision to return to grade. Observations and/or interpretations of bedrock terrace formation driven by upstream-propagating waves of incision (e.g., Brocard et al., 2003; Crosby and Whipple, 2006; Jansen et al., 2011; Pazzaglia and Gardner, 1993; Plumley, 1948; Zaprowski et al., 2001) lend support to the idea that sequences of terraces record impulsive changes in base level over time. Such pulses of incision can be triggered by relative sea-level fall (e.g., Castillo et al., 2013; Pazzaglia and Gardner, 1993), sudden tectonic uplift (e.g., Cook et al., 2012; Yanites et al., 2010), incision of channels downstream (e.g., Zaprowski et al., 2001), an increase in rock uplift rate (e.g., Whipple and Tucker, 1999; Whittaker et al., 2007), or an increase in erosional efficiency (e.g., Whipple et al., 1999). Additionally, pulses of local base-level lowering from meander cutoffs in bedrock channels generate flights of terraces and realistic terrace morphologies in a numerical model (Finnegan and Dietrich, 2011), again supporting the possibility of a base-level control on terrace formation. The

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apparent connection between base-level drop and strath terrace formation in many settings provides the essential basis for interpreting terrace formation in a tectonic context.

In contrast, although Bull (1990) also argued that strath planation occurred under conditions when supply and capacity were balanced, he was, to our knowledge, the first to propose that strath terrace formation could occur in the absence of impulsive base-level forcing. Specifically, Bull (1990) argued that in tectonically active channels, climate-driven sediment aggradation results in a cessation of vertical incision and hence in surface uplift of the channel relative to base level. Terrace formation occurs once the channel excavates back through its sedimentary cover and cuts vertically at an accelerated rate to return to base level. The magnitude of incision into the strath, in this view, is a function of the local rock uplift rate and the duration of time over which the strath is buried in sediment. The significance of this hypothesis is its suggestion that both strath planation and strath terrace formation could occur entirely by climatic forcing of sediment supply relative to river transport capacity rather than by impulsive tectonic forcing of base level (Bull and Knuepfer, 1987). Bull's (1990) conceptual model helps explain why, in some settings, strath terraces are buried in up to tens of meters of sediment and appear to have formed from rapid vertical incision into bedrock. Several studies have presented field (Garcia, 2006; Pazzaglia and Brandon, 2001) and geochronologic evidence (Fuller et al., 2009) as well as numerical modeling (Hancock and Anderson, 2002) supporting this conceptual model. Additionally, numerous studies showing strath terrace formation on glacial-interglacial time scales (e.g., Chadwick et al., 1997; DeVecchio et al., 2012; Molnar et al., 1994; Pan et al., 2003; Pazzaglia and Brandon, 2001) lend further support to a connection between strath terrace formation and climatic forcing of sediment supply.

However, recognition that strath terraces are commonly veneered with a thickness of sediment that is no greater than what is typically transported in a flood (Mackin, 1948; Wegmann and Pazzaglia, 2002) suggests that strath terrace formation in some settings does not require deep burial of straths in sediment. This point is underscored by the observation that the strath planation and valley widening in some bedrock channels are temporally coincident with deep aggradation in alluvial channels nearby (Molnar et al., 1994; Wegmann and Pazzaglia, 2009). Because mass conservation dictates that variation in sediment supply relative to transport capacity should drive channel aggradation and incision in alluvial channels (Parker, 2005), it is a straightforward step to relate alluvial terrace formation to climate-driven variability in sediment supply relative to transport capacity (e.g., Bridgland and Westaway, 2008; Bull, 1990). However, why sediment supply increases would also trigger valley widening in bedrock channels (as opposed to aggradation) lacks a straightforward mechanistic explanation. Although modest changes in width might result from sediment supply–driven adjustments in hydraulic geometry (Turowski et al., 2008), paired strath terraces that are commonly many times wider than river channels (Mackin, 1948; Molnar et al., 1994) cannot be explained by channel width change alone. Similarly, although bedrock meandering provides a mechanism for moving a bedrock channel laterally within a valley (Finnegan and Dietrich, 2011; Merritts et al., 1994), meandering alone does not create paired terraces or terraces that are typically wider than active channels (Finnegan and Dietrich, 2011).

BRAIDING AS A MECHANISM FOR STRATH PLANATION

In alluvial channels with floodplains, however, it is widely recognized that rapid growth in valley width can occur with a change from single-threaded to braided channel conditions (e.g., Carson, 1984). The threshold for transition from a single-thread to a braided channel state is marked by the breakdown of a single set of alternate bars along a channel into multiple bars across a channel (Parker, 1976). In his stability analysis of braiding, Parker (1976) identified four parameters that define this stability point: channel width, slope, dimensionless friction, and grain size. Either a decrease in the ratio of grain size to width or an increase in channel slope relative to dimensionless friction can trigger braiding (Parker, 1976). This framework helps to explain why, for instance, a meandering channel will braid when its width grows due to a cutbank erosion rate that exceeds the point bar deposition rate (Braudrick et al., 2009). Once the channel has grown sufficiently wide to initiate braiding, transition from meandering to braiding commonly occurs via cutoff of the chute formed on the inside of point bars (Ashmore, 1991; Carson, 1984), an event for which the proximal trigger is often the arrival of a pulse of sediment that redirects flow over the point bar and increases the water-surface elevation upstream of the chute (Ashmore, 1991).

In a meandering alluvial channel, cutbank erosion and point bar deposition are coupled via the flow and morphodynamics in the channel, usually resulting in the maintenance of a roughly constant width channel (Parker et al., 2011). However, cutbank erosion in many meandering bedrock channels appears to be a weathering-limited phenomenon (Johnson and Finnegan, 2011), suggesting that point bar deposition and cutbank erosion may be less well coupled than in a meandering alluvial channel. Additionally, field observations in regions of bedrock meandering suggest that channel banks weather to suspended or wash load (and during bank failures shed gravel material that quickly falls apart due to wetting and drying; Johnson and Finnegan, 2011). For these reasons, there may be little negative feedback on cutbank erosion in a meandering bedrock channel. Thus, braiding in an actively meandering bedrock river canyon can be initiated at bends where erosion on the outer bank has widened the channel into the braiding stability regime. Once the channel has braided, significant valley widening can occur simply because of the potential for erosion to occur on both banks of the river simultaneously—a condition that would be otherwise prevented by protection of the inner bank by the point bar in a purely meandering channel (Johnson and Finnegan, 2011). A return to single-thread channel conditions, in turn, could account for bedrock terrace formation. This situation is an ideal one to preserve terraces along valley wall margins, as is required for the formation of paired strath terraces, because a shift from braided to single-thread channel conditions is accompanied by both narrowing of the zone of active bed-load transport on the valley bottom (e.g., Carson, 1984) as well as vertical incision (Gran, 2010; Leigh, 2006).

Here, we hypothesize that in bedrock channels, a transition from a single-thread meandering state to a braided state provides a mechanism for valley widening and strath cutting, whereas a return to a single-thread meandering state can account for narrowing and strath terrace formation. Our hypothesis relies on the fact that significant valley widening by terrace-forming rivers is possible in weak and easily weathered rocks (Montgomery, 2004). Although the mechanics of lateral erosion into bedrock are not well established, observed rates of lateral erosion in fractured mudstone approach 1–10 cm/yr (Fuller et al., 2009; Suzuki, 1982), suggesting that where rivers are cutting mudstone, the bedrock walls may offer little more resistance to lateral motion than would cohesive floodplain sediments. We note that most rock terraces form in mudstone or other weak sedimentary rocks (Montgomery, 2004).

APPROACH

In order to evaluate the hypothesis that transitions between single-thread and braided channel conditions can account for both strath planation and strath terrace formation, as well as explore the various conceptual models for strath terrace formation, here we focus on Arroyo Seco in the central California Coast Ranges. Our choice of this field locale is guided by Arroyo Seco's geologic setting, its exceptionally well preserved and exposed bedrock terraces, and the availability of airborne laser swath mapping (ALSM) data over the portion of the river where terraces are preserved. We use an objective light detection and ranging (LiDAR)–based terrace identification algorithm to map strath terrace long profiles and one-dimensional LiDAR-based hydraulic modeling to quantify flow conditions in Arroyo Seco's current channel, much of which is braided. Along with observations of terrace morphologies revealed by LiDAR, these analyses support transition from single-thread to braided conditions as a mechanism for strath planation. Our results suggest that strath terrace formation, in turn, appears to be driven by pulses of vertical incision into downstream alluvial sediments that then propagate upstream into bedrock, causing abandonment of active straths.

STUDY SETTING

Arroyo Seco is a sinuous bedrock channel that drains a 630 km^2 unglaciated catchment that flows into the Salinas River from the east side of the Santa Lucia Range of central California (Fig. 1A). It crosses the active transpressional Reliz Canyon fault, which separates upthrown bedrock from a clastic sediment fill in the adjacent, downthrown, Salinas River basin (Snetsinger, 1962) (Fig. 1A). Although detailed constraints on motion of the Reliz Canyon fault are lacking, the fault is thought to have been active in the late Pleistocene and is primarily thrust sense in motion (Rosenberg, 2005). Upstream of the fault and downstream of where the river exits the crystalline core of the Santa Lucia Range, prominent paired strath terraces are etched into the mudstone of the Miocene Monterey Formation (Snetsinger, 1962) (Figs. 1B–1C). Like typical settings where bedrock terraces are observed (Montgomery, 2004), the mudstone of the Monterey formation is weak and highly fractured over most of the study region.

METHODS

Terrace Identification

We use a 5-m-pixel resolution LiDAR-derived "bare-earth" digital elevation model (DEM) to identify and quantify the planform morphology of the Arroyo Seco terraces. Specifically, because terrace identification and correlation are notoriously ambiguous (Merritts et al., 1994; Seidl and Dietrich, 1992), here we devised a simple means of objectively identifying terraces from LiDAR-derived topography data. Our approach relies on the fact that the elevation distribution of a valley with terraces is distinct from the elevation distribution of a valley with planar hillslopes (Fig. 2). After dividing the topography orthogonal to the river into equally spaced vertical bins, it is straightforward to see that a terrace will contribute more DEM cells to a given elevation bin than would a planar hillslope (Fig. 2). Plots of the frequency of binned elevation orthogonal to a river channel plotted against river length thus provide a novel and objective means of revealing patterns in terraces along river valleys. This approach represents an improvement over a previous effort to objectively map terraces (Demoulin et al., 2007) in that it does not rely on spatial derivatives of topography, which tend to be noisy.

We extracted a swath of LiDAR-derived topography data parallel to Arroyo Seco that roughly corresponds to the region of the landscape where terraces are visible (Fig. 1A). We downsampled the original 1-m-pixel resolution LiDAR-derived DEM to 5-m-pixel resolution to improve computational efficiency and minimize noise. We then digitized a valley axis profile for the river in the Salinas Valley, and combined it with a thalweg profile of the river in the canyon reach. We extracted points at 100 m intervals along the profile and then assigned every pixel in the DEM of the river canyon to the closest point along the river/valley profile. Finally, we binned the topography into 2 m vertical increments and then computed the normalized frequency within each population of DEM cells assigned to a specific location along the river/valley profile (for source code of terrace-finding algorithm, see GSA Data Repository material[1]).

Because strath terrace levels are blanketed by a variable thickness of gravel downstream, our measured elevation includes both the elevation of the bedrock strath as well as the fluvial deposits capping it (Fig. 3A). In Arroyo Seco, sediments capping straths do not typically exceed 2–3 m in thickness (Snetsinger, 1962; Taylor, 2010). Consequently, the uncertainty in terrace level owing to variable sediment thickness, alone, is probably no more than a few meters. A potentially more significant source of uncertainty in mapping terrace elevations, however, is that older strath terraces are often buried by many meters of debris-flow deposit. Because debris-flow fans are steeper than terraces, we expect they diffuse the crisp elevation signals associated with the flat terrace surfaces on which they are deposited. Additionally, because fans raise the mean elevation of a terrace, a fan-covered terrace will have a higher top surface elevation than a terrace, in addition to having a smaller normalized frequency than a terrace of the same width. Hence, elevation bands with high normalized frequency may represent terraces capped with significant accumulations of debris. For this reason, we restricted our analysis to the lowest and most recently formed terrace in Arroyo Seco, because it is well preserved and has only minor debris-flow deposition on its surface (Fig. 3B).

[1]GSA Data Repository item 2013107, Matlab LiDAR terrace identification script, is available at http://www.geosociety.org/pubs/ft2013.htm or by request to editing@geosociety.org.

Hydraulic Modeling

We used one-dimensional hydraulic modeling to calculate the active width of the modern channel during a large flood and to objectively define braided reaches. Accordingly, we used HEC-GeoRAS (www.hec.usace.army.mil/software/hec-ras/hec-georas.html) to extract hydraulic geometry from the filtered 1-m-resolution "bare-earth" LiDAR data of Arroyo Seco's main-stem channel. We note that LiDAR does not penetrate the water surface; hence, the LiDAR-derived DEM does not resolve the entire river bathymetry. However, on the day of the LiDAR acquisition, the average discharge at the U.S. Geological Survey (USGS) gauge located at the mouth of the Arroyo Seco canyon (waterdata.usgs.gov/usa/nwis/uv?11151870) was 10 m^3/s (Fig. 4B). Because, as described in the following, we extracted channel width data from a modeled 10 yr recurrence interval flood, with a magnitude of 540 m^3/s at the USGS gauge (Fig. 4B), the effect of the small amount of submerged topography on the ultimate width calculations is likely to be minimal.

Cross-section lines were hand-digitized at an average downstream spacing of ~30 m, which is less than the average high-flow width of the channel, ~64 m. We used HEC-GeoRAS to generate input hydraulic geometry data for HEC-RAS (www.hec.usace.army.mil/software/hec-ras/index.html) in order to model floods within the Arroyo Seco canyon.

This study benefits from a 104 yr record of peak annual discharge measurements from the USGS gauge at the lower end of Arroyo Seco's canyon (waterdata.usgs.gov/usa/nwis/uv?11151870). We calculated an empirical flood magnitude recurrence period curve (Dunne and Leopold, 1978) for 104 yr of annual peak flood data (Fig. 4A). The empirical fit to the data was then used to calculate the discharge at the gauge for a representative large recurrence interval flood, which in the analysis presented later herein corresponds to a 10 yr recurrence

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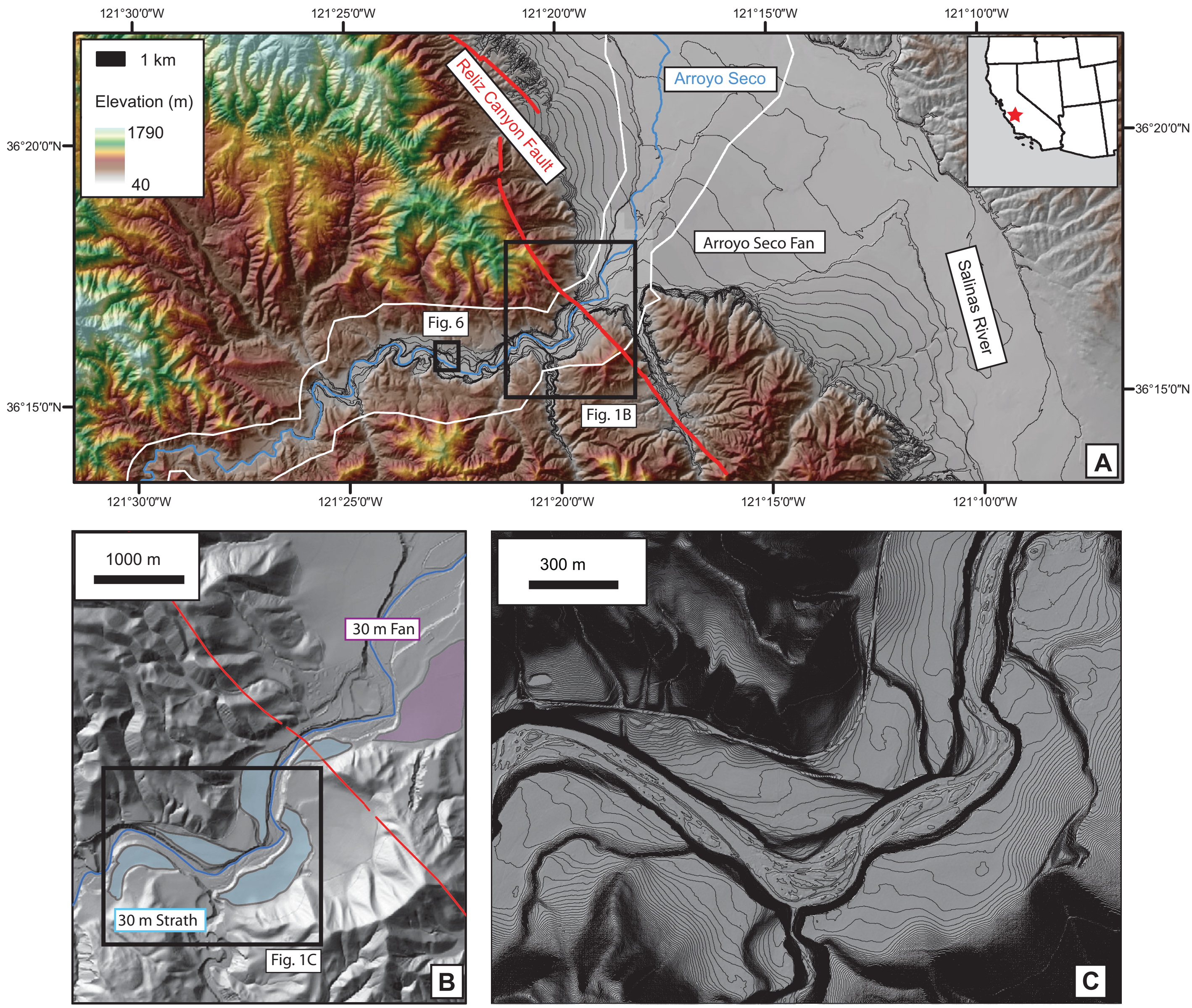

Figure 1. (A) Overview of the study area. The white line encloses the domain used in the terrace extraction algorithm. The blue line indicates the location of Arroyo Seco, and the red line is the location of the Reliz Canyon fault (U.S. Geological Survey Quaternary Fault Database). Contours in the Salinas Valley are 10 m. (B) Shaded relief image derived from light detection and ranging (LiDAR) data for the lower Arroyo Seco canyon. The 30 m terrace level is mapped in blue, and the 30 m fan is in purple. The Reliz Canyon fault is again indicated with the red line. (C) Shaded relief close-up of the 30 m terrace immediately upstream of the Reliz Canyon fault. Contour interval is 1 m. Several point bars that have experienced chute cutoff and are now isolated from the valley walls on both sides are visible.

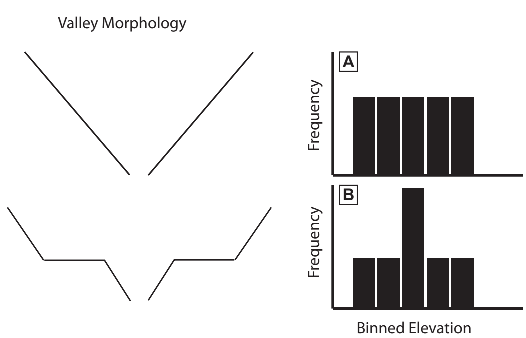

Figure 2. Schematic valley elevation cross sections (left) and associated elevation frequency histograms for non-terraced (A) and terraced valley (B).

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interval. We note that the specific choice of a 10 yr recurrence interval flood was somewhat arbitrary. Our goal was to model a flood that would fill the various threads within the braided reaches of Arroyo Seco without completely overtopping the vegetated (and hence infrequently inundated) alluvial deposits between them. However, we emphasize that a range of flood magnitudes meets this criteria.

To define discharge at each cross section in the calculation, we assumed spatially uniform runoff during storms and hence a linear scaling between drainage area and discharge. The slope of the scaling relationship came from using discharge at the USGS gauge and an assumption that at zero drainage area, there is zero runoff. We chose a roughness length scale of 10 cm for flow calculations, in keeping with the D_{84} of bed load in Arroyo Seco. In the model, contraction and expansion coefficients were set to 0.1 and 0.3, respectively. Upstream and downstream boundary conditions were determined by calculating the water-surface elevation after assuming a Froude number of 1. The domain we model is over 30 km in length. Therefore, the details of the treatment of the upstream and downstream boundary conditions, which influence only a few tens of meters upstream and downstream of the boundaries, are not critically important to the synoptic analysis here. Because Arroyo Seco is braided in many sections, we output the width between the left and right banks of the threads that were most separated in space (Fig. 5B). Although this is the relevant width for valley formation processes, it is not the same as the actual width of flooded channel, which is much less than what is reported in Figure 5B for braided reaches. Additionally, in order to define braided reaches objectively, we used the output of the hydraulic model to identify reaches with more than two active channels. The rationale here is that a meandering channel at flood may diverge around the point bar, thereby occupying two channels. However, maintenance of three or more active channels is less straightforward to interpret in a meandering channel, whereas it is expected in a braided environment.

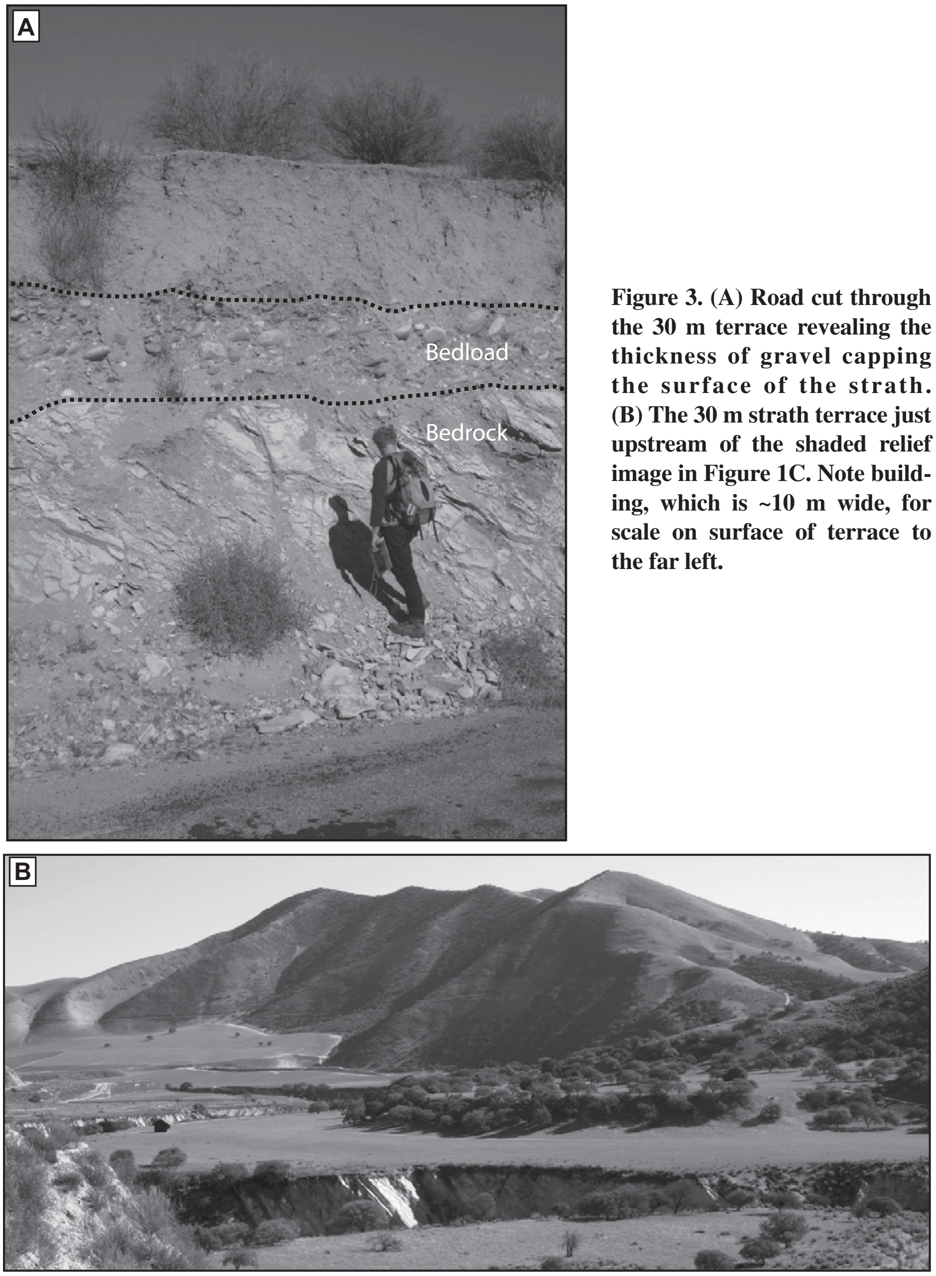


Figure 3. (A) Road cut through the 30 m terrace revealing the thickness of gravel capping the surface of the strath. (B) The 30 m strath terrace just upstream of the shaded relief image in Figure 1C. Note building, which is ~10 m wide, for scale on surface of terrace to the far left.

OBSERVATIONS/RESULTS

Results of the terrace identification algorithm reveal a prominent paired bedrock terrace (henceforth "the 30 m terrace"; Fig. 3B) that is ~30 m above the active channel (Figs. 5A and 5C) and traceable along ~25 km of the river upstream of the Reliz Canyon fault (Fig. 5A). The prominent terrace level revealed by the terrace identification algorithm matches a prominent low terrace recognized by Snetsinger (1962) and mapped over the same section of Arroyo Seco. Immediately upstream of the Reliz Canyon fault, the terrace is approximately four times the width of the active channel (Figs. 1B–1C). Although the active channel is primarily a single-thread, meandering bedrock channel here, high flow locally diverges around point bars (Fig. 1C). However, after moving another ~5 km upstream, the active channel of Arroyo Seco is fully braided (Figs. 5B and 6), and topographic evidence for the 30 m terrace, although present, is much less extensively preserved (Fig. 5A). Sparse terrace preservation in this reach is also indicated by Snetsinger's (1962) more speculative terrace correlations over the same section of river where we observe an absence of clear topographic evidence for longitudinally continuous terraces. Approximately 15 km upstream of the Reliz Canyon fault, the river returns to being primarily single threaded, and widespread topographic evidence for the 30 m terrace is once again present. Below the Reliz Canyon fault, the river remains entrenched, but within a fan composed of its own alluvium (Figs. 1A and 5A). The 30 m terrace grades into the fan surface with no offset across the fault (Fig. 5A). The bedrock terrace above the Reliz Canyon fault is parallel to the modern bedrock channel profile, but the fan surface is steeper than the modern channel incised into it (Fig. 5A).

Two knickpoints are developed along the profile of Arroyo Seco where it drains the crystalline

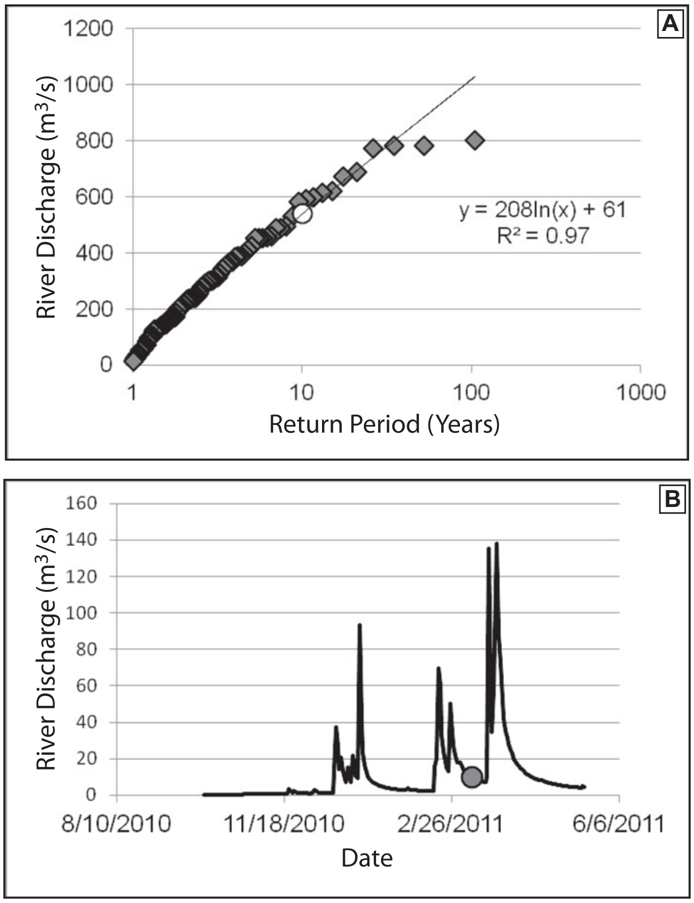


Figure 4. (A) Annual peak flood discharge vs. return period for the Arroyo Seco U.S. Geological Survey river gauge. White dot indicates the magnitude of the flood modeled in Figure 5B. (B) River discharge (gray dot) on the day of the acquisition of the light detection and ranging (LiDAR) data used herein compared to the seasonal pattern of discharge during winter and spring, 2010–2011.

interior of the Santa Lucia Range, at the far upstream end of the domain considered here (Fig. 5A). The crest of the lower and more prominent knickpoint appears to coincide in elevation with the 30 m terrace level (Fig. 5A).

Our (e.g., Fig. 2A) and others' (Taylor, 2010) observations show that gravel capping the strath nowhere exceeds 2–3 m in thickness and that cobbles in the modern channel are indistinguishable in size and composition from those capping strath terraces (Snetsinger, 1962).

DISCUSSION

Braiding and Strath Planation

Riverbed armoring during episodes of increased sediment supply is commonly argued to provide a mechanism for enhancing lateral planation in comparison to vertical incision (Gilbert, 1877; Hancock and Anderson, 2002; Mackin, 1948). However, our observations indicate that increased thickness of sedimentary cover is unlikely to explain the formation of the 30 m strath in Arroyo Seco. Immediately upstream of the Reliz Canyon fault, Arroyo Seco has cut a narrow gorge (Fig. 1C). At this location, one can compare a channel that is not currently forming a strath to adjacent deposits that record strath formation. LiDAR data reveal that gravel bars in the active channel here have 2–3 m of relief above the bed (Fig. 1C), which is comparable to the thickness of gravel capping strath terraces throughout the catchment (Taylor, 2010) (Figs. 2A–2B). Thus, the thickness of strath-capping gravel is not noticeably different compared to locations in the modern channel where straths are not forming.

Several lines of evidence, however, suggest that rivers were braided during planation of the 30 m strath. Field observations (e.g., Carson, 1984) indicate that braided channels transport sediment over a much wider section of valley than single-thread channels at the same discharge. In Arroyo Seco, strath terraces are commonly many times the valley width of sections of the modern river that are actively meandering (Figs. 1C). Similarly, sections of the canyon that are currently braided are much wider than paleochannels preserved within bedrock meander bend cutoffs (Fig. 6). Because maintenance of a bedrock meander bend should require a single-thread channel (Finnegan and Dietrich, 2011), the observation that bedrock meander loop cutoffs are much narrower than braided reaches supports the hypothesis that a transition from meandering to braiding caused bedrock terrace planation. Additionally, in the locations where the modern channel is currently braided (Figs. 5B and 6), the 30 m terrace is much less well preserved than in the locations where the channel is not braided (Figs. 5A–5B). This preservation bias also supports the hypothesis that braiding is responsible for triggering strath planation because actively braided reaches have a similar width when compared to preserved strath terraces. Thus, in Arroyo Seco, evidence for past episodes of braiding, in the form of paired strath terraces, is apparently largely destroyed by subsequent episodes of braiding. This provides a simple explanation for why, although present, higher terraces in Arroyo Seco are generally not longitudinally continuous (Snetsinger, 1962). The fact that only the most recently formed terrace is well preserved along the river in turn supports the idea that terrace formation is triggered following narrowing associated with a return to single-thread conditions. Lastly, point bars in the narrower portion of Arroyo Seco's canyon that appear to have been isolated from the bedrock canyon wall by chute cutoff (Fig. 1C) are suggestive of the incipient stages of braiding described by Carson (1984) and Ashmore (1991), and thus indicate that our proposed mechanism for the transition from meandering to braiding in bedrock channels is viable.

Strath Abandonment and Terrace Formation

In this section, we consider the various conceptual models for strath terrace formation in the light of our geomorphic observations in Arroyo Seco. A common thread that unites the conceptual models for strath terrace genesis described in the introduction is that strath planation and strath terrace formation require temporally variable rates of vertical incision. Specifically, Gilbert (1877) and Davis (1909) argued that strath terrace formation occurs during periods of impulsive base-level drop, whereas Bull (1990) argued that terrace formation occurs during

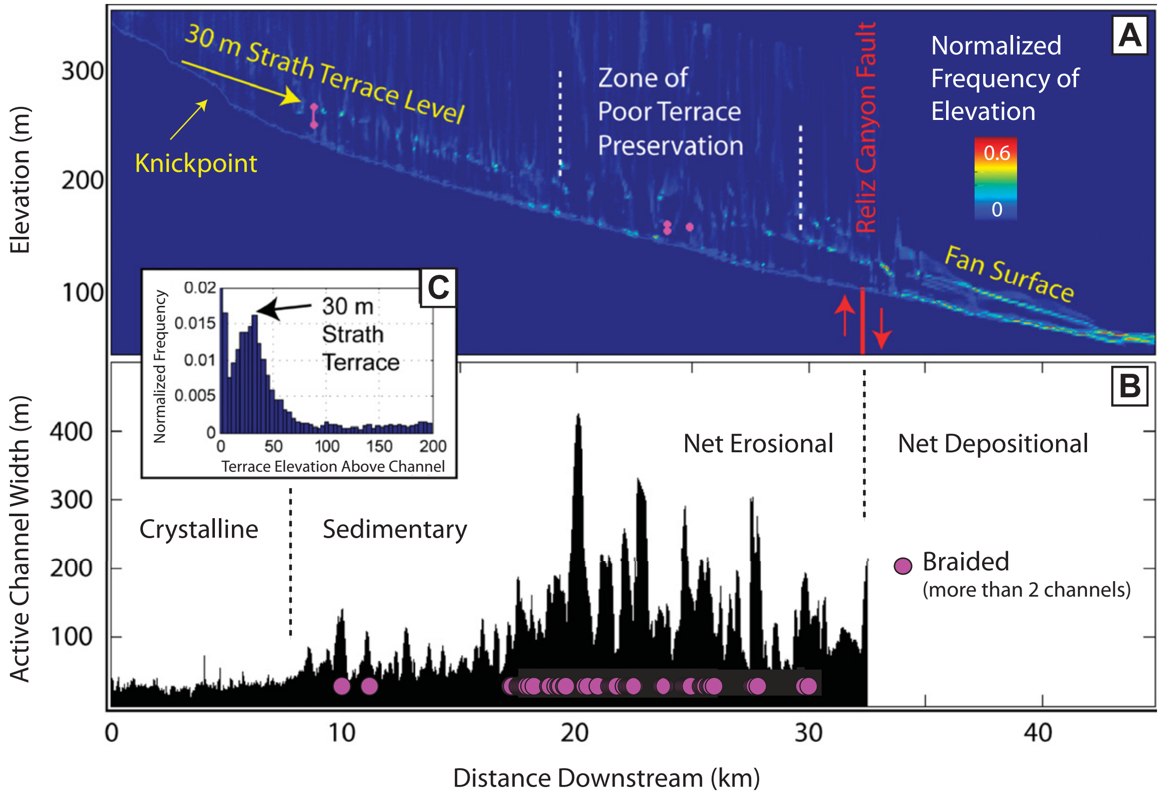


Figure 5. (A) Plot of normalized frequency of elevation along the Arroyo Seco corridor. Data are restricted to less than 150 m in elevation above the channel bottom. The red vertical line indicates the location of the Reliz Canyon fault, and the levels of the 30 m strath terrace and its correlative fan deposit are labeled in yellow. Pink dots show the location of abandoned bedrock meander cutoffs, and the vertical separation between pink dots indicates the estimated elevation drop around the paleo–meander bend. (B) Width between the left and right banks of the active channel threads that were most separated in space during a modeled 10 yr recurrence interval flood. The plot highlights the braided reaches of Arroyo Seco, which have both a higher average width and a higher width variance. (C) In order to isolate terrace data, we extracted elevations from part A that correspond to normalized frequencies greater than 0.025. Figure 1C shows a histogram of the normalized frequency of these terrace elevation data after the elevation of the adjacent river channel has been subtracted. The sharp peak in the histogram centered on ~30 m indicates that the height of the most prominent terrace is consistent downstream and thus possible to correlate downstream. The sharp peak near 0 m is the active river valley bottom.

periods of rapid incision to base level following burial of the channel under sediment. The results of our LiDAR analysis also allow us to constrain recent changes in rates of vertical incision at Arroyo Seco. Specifically, because the 30 m terrace grades into a steeper alluvial channel than the modern bedrock channel in Arroyo Seco (Fig. 5A), we can infer that the mouth of Arroyo Seco's canyon was higher in elevation when the 30 m strath formed compared to today (Fig. 5A). This is a simple geometric requirement of the fact that the 30 m fan head must have been higher in elevation in order for it to maintain a steeper profile (Fig. 5A). However, this observation shows that Arroyo Seco's bedrock channel has lowered in absolute elevation by ~30 m since the formation of the 30 m strath, implying that over the recent geologic past, Arroyo Seco has incised at a more rapid rate than the rate of rock uplift on the Reliz Canyon fault. We emphasize that a steady-state channel where rock uplift and incision rates are balanced does not change absolute elevation in time. Thus, topographic evidence shows that the most recent strath terrace formed in Arroyo Seco following a period of rapid vertical incision.

Although tectonic forcing of river base level is a common explanation for rapid incision and strath terrace formation (e.g., Cook et al., 2012; Yanites et al., 2010), we can rule out tectonic forcing of base level as a mechanism for forming the 30 m strath terrace here because it grades into depositional terraces across the Reliz Canyon fault (Fig. 5A). Thus, lateral planation of bedrock occurred at the same time as aggradation downstream. Subsequent vertical incision has occurred both upstream and downstream of the fault, but not because of the fault. If fault motion were responsible for driving incision upstream, vertical incision (and thus terraces) would terminate downstream at the fault. We can also rule out sea-level forcing as a potential explanation for terraces because vertical incision into the Arroyo Seco fan decreases to near zero at the junction with the Salinas River (Fig. 5A). If incision were triggered by sea-level fall in Monterey Bay, the Salinas River should record the same amount of vertical incision as Arroyo Seco. Lastly, we reject meander migration and cutoff as an explanation for strath planation and subsequent terrace formation. This is because terraces are present downstream of mapped meander cutoffs, which shows that vertical incision propagated upstream from

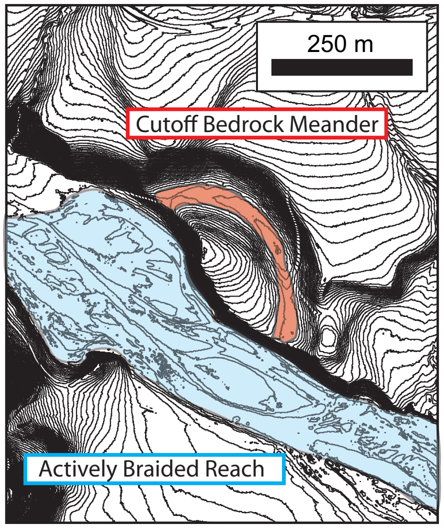


Figure 6. Contour map of a braided section of the active channel adjacent to an abandoned bedrock meander cutoff. Contour interval is 1 m. Location of the map is shown in Figure 1A.

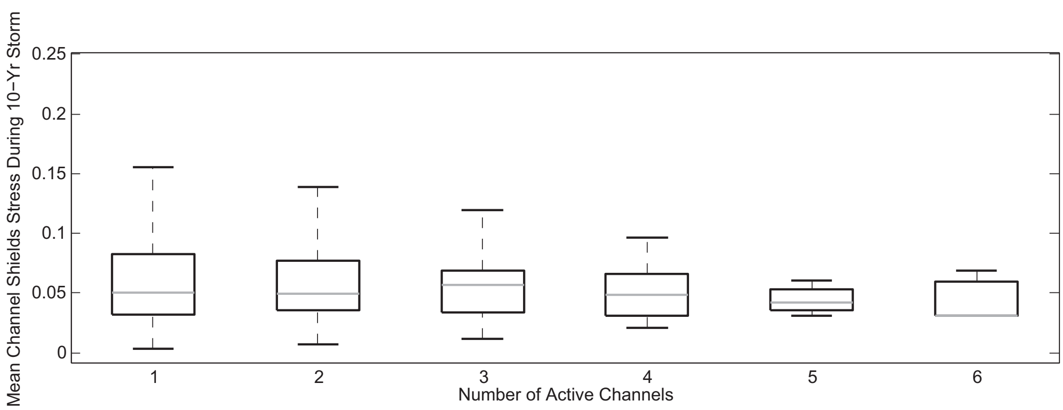
meander cutoffs cannot explain terrace formation (Fig. 5A). Additionally, the magnitude of vertical incision recorded by the 30 m terrace is much larger than the elevation drop around any of the preserved meander bends (Fig. 5A), providing further evidence against meander cutoff as an explanation for terrace formation.

Bull (1990) argued that terrace formation occurs once a channel excavates back through a thick (tens of meters) sedimentary cover and cuts vertically at an accelerated rate to return to base level. This model is, however, incompatible with the evidence in Arroyo Seco simply because the gravel capping the straths, as noted earlier, does not exceed 2–3 m and is on the order of the thickness of bars deposited in locations of the channel where straths are not currently forming (Fig. 1C). More generally, the geomorphic evidence in Arroyo Seco does not support sediment supply as a direct driver of strath terrace planation and abandonment here. The 30 m bedrock terrace grades into a depositional terrace that is steeper than the modern river valley in the Salinas Valley (Fig. 5A). Alluvial channel steepening is a common response to increased relative sediment loads, and deep aggradation, which is required by steepening, fundamentally requires sediment supply in excess of transport capacity (Parker, 2004). Thus, the 30 m strath appears to have formed under increased relative sediment supply. In contrast, the modern bedrock channel in Arroyo Seco, which is braided over much of its distance and is presumably currently forming a strath (Fig. 5A), grades into a lower-gradient alluvial channel that is incised into the fan (Fig. 5A), suggesting current sediment loads are comparatively lower than when the 30 m strath was cut. Thus, in Arroyo Seco, strath planation apparently occurs during intervals of both relatively high and relatively low sediment supply, suggesting sediment supply does not influence terrace formation in a straightforward way.

A possible alternative explanation for the apparently lower vertical incision rates during braiding and terrace planation, despite the absence of a detectable change in alluvial cover thickness, is that under braided conditions, Arroyo Seco exerts a lower stress on its bed. This is plausible because braided channels are generally shallower than meandering channels at an equivalent discharge. To test for this possibility, we use the results of the hydraulic modeling to plot mean channel shear stress as a function of the number of active channels along Arroyo Seco (Fig. 7). Figure 7, however, shows no discernible difference between bankfull stresses in single-thread and multiple-thread channels along Arroyo Seco's modern channel, suggesting that a transition between meandering and braiding, alone, cannot explain the changes in vertical incision rate that are required by the geomorphic observations in Arroyo Seco. On the contrary, Arroyo Seco appears to be graded to exert a Shields stress at flood that is exactly in the range expected for a gravel bed channel (~0.05) (Parker, 2004).

Because none of the conceptual models completely explains the formation of the 30 m terrace in Arroyo Seco, here we offer an alternative conceptual model for strath planation and abandonment in Arroyo Seco. We note that aggradation and incision of alluvial sediments downstream of the Reliz Canyon fault, which has driven ~30 m of recent elevation change (Fig. 5A), provide a potentially strong local base-level control on the bedrock section of Arroyo Seco upstream of the Reliz Canyon fault. If fan aggradation downstream of the Reliz Canyon fault occurred at approximately the same rate as tectonic uplift on the Reliz Canyon fault, it could effectively buffer Arroyo Seco's bedrock channel from the drop in relative base level that would otherwise occur due to fault motion (Fig. 8B). Periods of aggradation along Arroyo Seco's alluvial channel could therefore inhibit vertical incision of bedrock upstream, and thus promote the lateral channel erosion that is required to trigger braiding. Fan incision under decreased sediment supply, such as apparently occurred to form the 30 m terrace, in turn, would result in the exhumation of a bedrock step at the fault, the relief of which would correspond to the accumulated slip on the fault during fan aggradation (Fig. 8C).

Figure 7. Box and whisker plot of Shields stress plotted as a function of the number of active channels during the 10 yr recurrence flood modeled in Figure 5B. The data are taken only from the portion Arroyo Seco where it is cutting sedimentary rocks and therefore carving straths. The D_{50} in Arroyo Seco is 7 cm. The top and bottom edges of the boxes are the 25th and 75th percentile values of Shields stress, the gray line corresponds to the median Shields stress, and the whiskers contain 99.3% of the total data distribution.



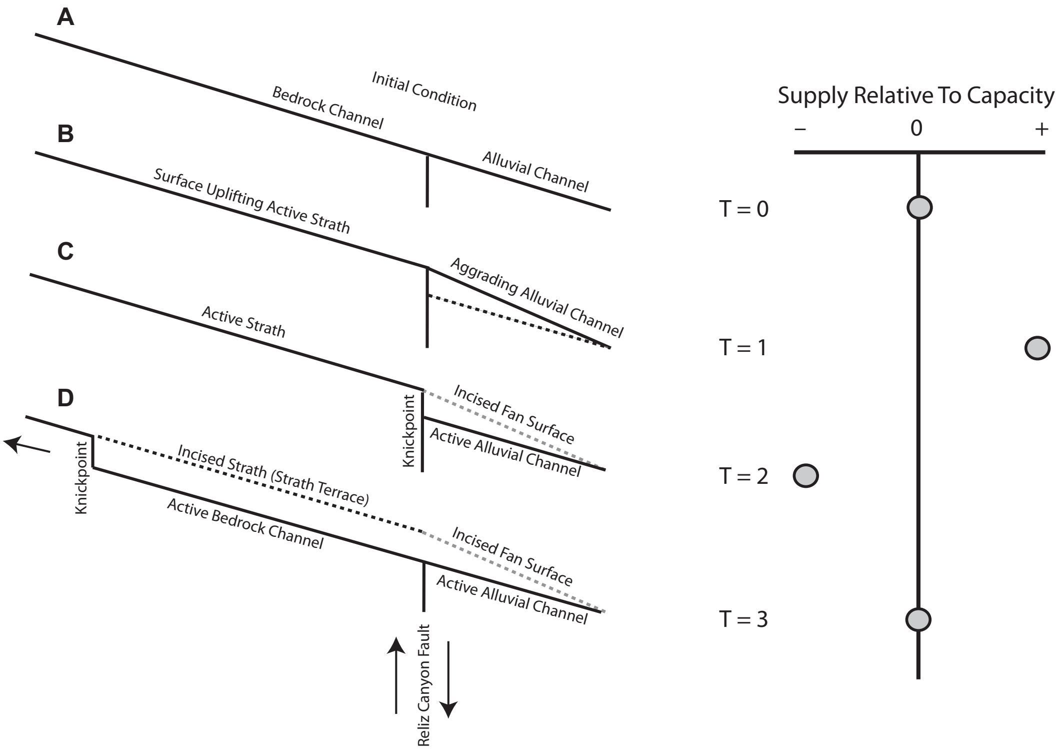


Figure 8. Conceptual model for strath planation and strath terrace formation in Arroyo Seco driven by aggradation and incision of fluvial sediments in the Salinas Basin.

Propagation of this step upstream as a knickpoint could trigger strath abandonment and thus strath terrace creation upstream of the fault (Fig. 8D). Because knickpoint propagation is commonly associated with channel narrowing (Sklar et al., 2005; Yanites et al., 2010), propagation of a knickpoint upstream through a braided channel network represents an attractive mechanism to generate paired strath terraces.

Several aspects of the geomorphology of Arroyo Seco support this conceptual model. In particular, a prominent knickpoint in the crystalline portion of Arroyo Seco's long profile has approximately the same relief above Arroyo Seco's modern channel as the 30 m terrace (Fig. 5A). This is consistent with the upstream propagation of a knickpoint from the Reliz Canyon fault that is now stalled on the much harder rocks of the Salinian basement of the Santa Lucia Range. In addition, downstream of this knickpoint, much of Arroyo Seco is currently braided and is presumably forming a strath despite apparently lower sediment supply relative to when the 30 m terrace formed. Our conceptual model suggests that intervals of high sediment supply in Arroyo Seco should result in little or no relative base-level lowering in Arroyo Seco because of aggradation in the Salinas Valley (Fig. 8B). Additionally, according to the conceptual model, the present should also be a period of relatively modest vertical incision rate along the ~30 km of the river considered here. This is because the wave of incision that apparently formed the 30 m terrace is now far upstream (Fig. 8D). The fact that Arroyo Seco formed straths both during aggradation of its downstream fan as well as after incision into this fan therefore suggests that base-level stability is the most direct cause of strath planation in Arroyo Seco. Although base level here is itself related to sediment supply via aggradation and incision of Arroyo Seco's fan, sediment supply alone, as noted already, does not appear to have a direct influence on strath planation, as evidenced by the fact that straths formed along Arroyo Seco during both high and low relative sediment supply.

In most respects, the conceptual model articulated here is similar to that proposed by Bull (1990). The key difference is that in Arroyo Seco, the hiatus in vertical incision during formation of the 30 m strath was apparently driven by aggradation on the downthrown side of the Reliz Canyon fault, rather than by burial of the active strath itself. In other words, Arroyo Seco's channel apparently had enough excess sediment transport capacity at the time of the 30 m strath formation to allow an increase in sediment transport efficiency without transient aggradation in bedrock. Alternatively, excess sediment was accommodated in Arroyo Seco not by vertical aggradation of the channel, but instead by lateral channel motion and bar deposition. This would help explain the presence of wide bedrock terraces with thin gravel veneers, as observed in Arroyo Seco and elsewhere. However, examples of buried straths in numerous settings (Bull, 1990; Pazzaglia and Brandon, 2001) suggest a limit to the sediment storage potential provided by strath planation alone.

CONCLUSIONS

We used LiDAR-derived topographic data, field observations, and hydraulic modeling both to explore conceptual models for strath terrace formation and to test the specific hypothesis that strath terraces record periods of braiding in bedrock channels. Our study focused on Arroyo Seco in the central California Coast Ranges, a location with exceptionally well-preserved paired strath terraces.

Our results support the idea that straths form when a river channel crosses the threshold from a stable single-thread to a braided channel. Specifically, the width of the most recently formed terrace in Arroyo Seco is comparable to the width of currently braided channels. Additionally, a comparison of currently braided reaches to abandoned bedrock meander cutoffs shows that braided channels have valleys that are several times wider than single-thread meandering bedrock channels. Lastly, in locations where the modern channel is currently braided, terraces are poorly preserved, suggesting that evidence for past episodes of braiding, in the form of paired strath terraces, is apparently eroded by subsequent episodes of braiding.

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Our results show that temporal variation in tectonic uplift rate, sea level, or alluvial cover along the river cannot explain strath planation and subsequent terrace formation in Arroyo Seco. Rather, our results provide evidence that aggradation and degradation of alluvial sediments downstream of the Reliz Canyon fault superimposed on steady rock uplift result in impulsive base-level forcing of Arroyo Seco's bedrock channel. Strath abandonment and terrace formation occur as incision into downstream alluvial sediments propagates upstream into bedrock. Braiding and planation of straths occur during intervals of low vertical incision rate associated with downstream aggradation or immediately following pulses of vertical incision triggered by downstream incision of alluvial sediments.

Our conceptual model for Arroyo Seco is similar to that proposed by Bull (1990). However, a key difference is that in Arroyo Seco, hiatuses in vertical incision are apparently driven by aggradation on the downthrown side of the Reliz Canyon fault, rather than by burial of the active strath itself.

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