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The dynamic reference frame of rivers and apparent transience in incision rates

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ABSTRACT

Incision rates derived from river terraces are commonly used to infer rock uplift rates; however, an apparent dependence of incision rate on measured time interval may confound directly relating incision to uplift. The time-dependent incision rates are a Sadler effect that have been argued to result from a stochastic distribution of hiatal intervals in river incision, potentially reducing the utility of incision records for interpreting unsteadiness in tectonic processes. Here we show that time-dependent incision rates can arise from a simple systematic bias in the distance measurement used to calculate incision rate, and thus stochastic causes are not required. We present a conceptual model that describes the dynamic history of streambed elevation over cycles of terrace formation, illustrating that measured incision rate is time dependent because the stream channel reference frame is not fixed with respect to the geoid. Because it is challenging to reconstruct the full elevation history for a river channel, most researchers use the modern streambed elevation as a reference datum, but we demonstrate that doing so imposes a bias that manifests as an apparent dependence of rate on measured time interval. Fortunately, correction of this bias is straightforward, and allows river incision data to be used in studies of tectonic or climatic unsteadiness.

INTRODUCTION

Landscapes reflect the competition between processes of rock uplift and erosion. In nonglaciated regions where tectonics build mountains, river incision is the dominant mechanism governing landscape denudation (Howard et al., 1994; Whipple, 2004). Over long time scales (>10^6 yr) with steady tectonic forcing, river gradients will adjust so that rates of bedrock incision equal rock uplift rates (Merritts and Vincent, 1989; Snyder et al., 2000). In these settings, river terraces are commonly used to quantify incision and infer rock uplift (Pazzaglia, 2013). However, river incision is not a steady process, as climatic, autogenic, and/or stochastic (e.g., mass-wasting) processes modulate discharge and sediment supply, resulting in periods of bedrock erosion and times of lateral planation and/or channel aggradation where vertical incision is negligible (Bull, 1991; Korup, 2006). It is this alternation between vertical incision and lateral planation or deposition that produces the river terraces from which incision histories can be derived (Pazzaglia and Brandon, 2001; Hancock and Anderson, 2002; Wegmann and Pazzaglia, 2002, 2009). Interpreting rates of rock uplift from the noise of unsteady incision remains a challenge in tectonic geomorphology studies.

The dependence of process rate on measured time interval has long been recognized in geological phenomena and is commonly referred to as the Sadler effect (Sadler, 1981; Schumer and Jerolmack, 2009). Computation of the power-law relationship between measured distance and time interval is a test normally used to identify the Sadler effect, while avoiding autocorrelation when plotting rate versus its own denominator (Gardner et al., 1987; Mills, 2000; Finnegan et al., 2014). In such cases, the Sadler effect is functionally any significant deviation from unity in the power-law exponent (β) of log duration versus log distance.

The mechanisms that give rise to the Sadler effect are still a matter of investigation. Most researchers follow Sadler's (1981) postulation that it arises due to intermittency in hiatal or depositional intervals (Schumer and Jerolmack, 2009). Many argue that the Sadler effect is related to a stochastic, heavy-tailed distribution of hiatal intervals in sediment deposition (Jerolmack and Paola, 2010) or river incision (Finnegan et al., 2014); however, Sadler (1981) showed that deterministic and cyclic forcing can also give rise to the effect.

An apparent dependence of rate on measured time interval is observed for river incision records on time scales approaching 10^7 yr (Mills, 2000; Finnegan et al., 2014). If it is confirmed that this fluvial Sadler effect is the result of stochastic hiatal intervals in river incision, the relationship between incision rate and rock uplift rate is unclear, and interpretations of tectonic unsteadiness are suspect (Finnegan et al., 2014). Although relatively well explored for stratigraphic records (Schumer and Jerolmack, 2009; Jerolmack and Paola, 2010), the exact processes that result in stochasticity of river incision over such broad time scales and across a diverse array of geologic and climatic environments remain speculative. For example, the impact of autocyclic factors (Finnegan and Dietrich, 2011) and stochastic processes, such as mass wasting (Korup, 2006) and extreme events like earthquakes and large storms (Wegmann and Pazzaglia, 2002; McPhillips et al., 2014), on long-term (10^6–10^7 yr) rates of river incision have not been conclusively demonstrated. Furthermore, such explanations do not address numerous observations in support of links between quasi-cyclic, deterministic climate forcing, and the formation of river terrace sequences, which can also account for time-dependent incision rates (Bull, 1991; Pazzaglia and Brandon, 2001; Hancock and Anderson, 2002; Pederson et al., 2006, 2013; Wegmann and Pazzaglia, 2009). Here we question whether the fluvial Sadler effect necessarily has anything to do with the temporal distribution of hiatal intervals, and explore alternative mechanisms that may give rise to time-dependent incision rates.

CONCEPTUAL FRAMEWORK AND MODEL DESIGN

It is necessary to distinguish between the process of river incision, which is erosion of the substrate (alluvium or bedrock) that floors a valley, and the measurement of incision, which is typically taken as the elevation difference between a terrace and the streambed. To avoid confusion of these two terms, we refer to the process of incision as erosion and the measurement of incision as incision or cumulative incision.

We begin with a conceptual model that describes the elevation history of a streambed at a given point on a river long profile, in a landscape undergoing steady rock uplift (Fig. 1A). Over the long term (10^6–10^7 yr), the river profile is assumed to be in steady state, such that the rate of river erosion equals rock uplift and the profile does not move up or down with respect to the geoid. On shorter time scales (10^3–10^5 yr) the river alternates between bedrock erosion and channel aggradation or lateral planation, when downward erosion is negligible, in response to changes in discharge and sediment supply (Hancock and Anderson, 2002; Wegmann and Pazzaglia, 2002). Streambed elevation rises during intervals of sedi-

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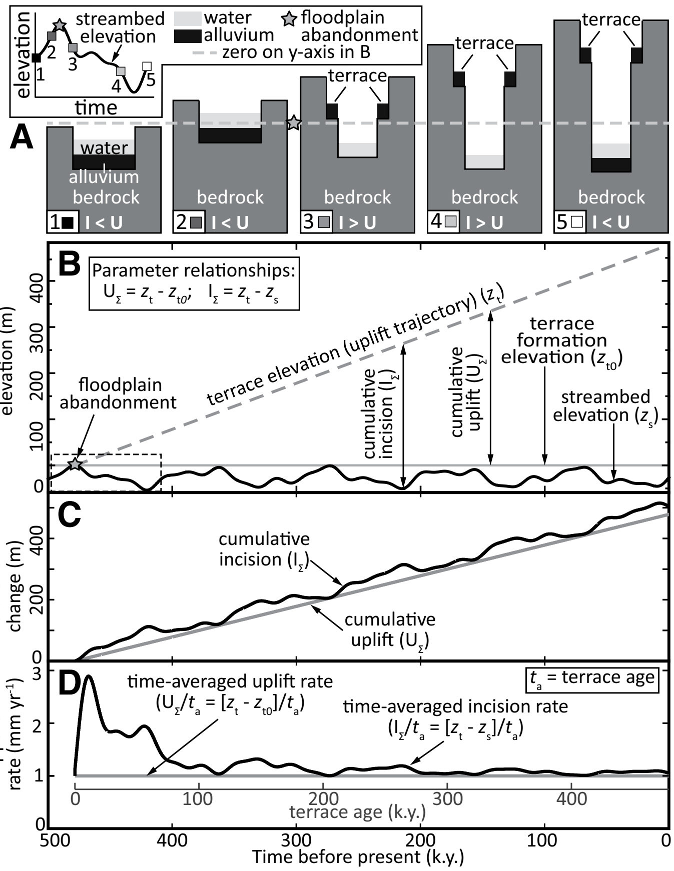

Figure 1. A: Conceptual model of dynamic base level and terrace formation (not to scale). Inset shows the hypothetical positions of the model in the context of the portion of the streambed elevation history shown in the black dashed box in B. I—incision; U—uplift. B: Streambed elevation history for the example of deterministic climate-like forcing (elevation is *z*). The channel elevation is assumed to be at the water-bedrock or water-sediment interface. Zero on the y axis is determined by the terrace formation elevation (gray star) and the terrace is uplifted from this position at 1 mm yr^{-1} (z_t; dashed gray line). C: Cumulative incision (I_S) and cumulative uplift (U_S) of a single terrace (z_t; dashed gray line in B) relative to the streambed elevation curve (z_s) and terrace formation elevation (z_{t0}), respectively, tracked from the time of terrace genesis (~480 ka) to the present day. D: Plot of time-averaged uplift and incision rate. Inset x axis shows the terrace age (t_a).

ment cover or aggradation when vertical erosion is arrested. Conversely, the active floodplain is abandoned, forming a terrace, when erosion commences and the streambed elevation falls (Fig. 1A).

It has long been recognized that the elevation of the streambed varies to accommodate terrace formation (Bull, 1991; Hancock and Anderson, 2002), but few studies address the mobility of the reference frame (the streambed) that is typically used to calculate incision (Pederson et al., 2006). The magnitude of streambed elevation variation is a function of a number of factors, including uplift rate, sediment flux, and discharge (Hancock and Anderson, 2002). In tectonically inactive low-relief landscapes the streambed elevation range will be low, likely on the order of several meters. In coastal settings that are rapidly uplifting it may be >100 m owing to changes in base level imposed by eustasy paired with rock uplift. Streambed elevation variability may be similarly high in landscapes with large hydrologic and sedimentologic changes in response to changing boundary conditions (e.g., climate), and channel aggradation will act to enhance the range of streambed elevation variability in a given setting.

To assess the impact of reference frame mobility on river incision records we use a rule-based model to explore two thought experiments (see the GSA Data Repository[1] for the full model description). The primary model inputs are an uplift rate, here set to a steady rate of 1 mm yr^{-1}, and a streambed elevation history (Figs. 1 and 2). River erosion is not explicitly modeled, but vertical erosion is assumed to occur when streambed elevation decreases and is arrested when it increases. We assume that the floodplain is abandoned and a terrace is formed at the upper inflection point in the streambed elevation curve, and the terrace is preserved only if it remains above the streambed elevation during the entire model run. Each model is run for 500 k.y. at 1 yr time steps.

As an illustration, we assume a streambed elevation history that mimics deterministic, climate-like forcing by compositing 3 sine waves with 16, 8, and 4 m amplitudes and 100, 41, and 23 k.y. periods, respectively; however, the temporal nature (stochastic or deterministic) of streambed elevation variability is relatively unimportant for the arguments presented here. We reason that the long-term uplift rate and the longest duration that vertical incision is arrested provide a means to approximate the amplitude of streambed elevation variability for strath terrace sequences. For example, based on the model uplift rate (1 mm yr^{-1}), if river incision is arrested for 50 k.y. (half the longest model forcing period), the local channel elevation will rise 50 m with respect to the geoid, which is the approximate summed amplitude of the streambed elevation curve used here.

EXPERIMENT ONE

This experiment illustrates measurements of incision and incision rate through time from the prospective of a single terrace generated at the first inflection point in the streambed elevation curve (ca. 480 ka) (Fig. 1B). The formation elevation of the terrace (zero on the y axis) is set as a fixed external reference frame (Fig. 1B). Two measurements are tracked during the model run, cumulative incision (I_Σ):

$$I_\Sigma = z_t - z_s, \tag{1}$$

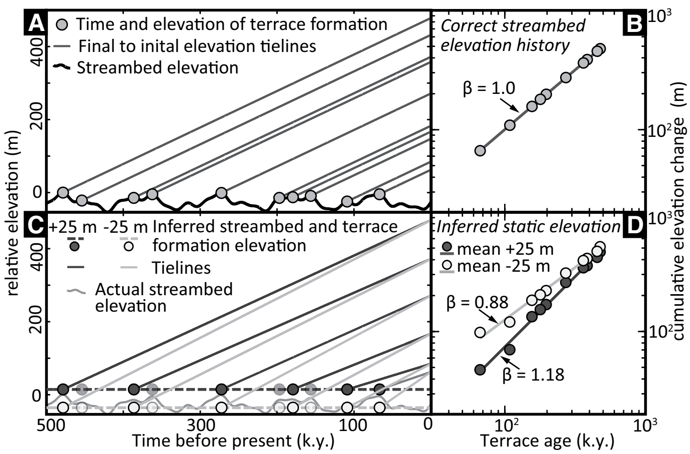

Figure 2. A: Elevation change since terrace formation calculated using local base-level history to link times of terrace formation. B: Log-log plot of terrace age and cumulative elevation change. C: Elevation change since terrace formation assuming two different static base levels, one 25 m higher (dark gray) and one 25 m lower (light gray) than the mean elevation of terrace formation (~–11 m). Tie lines are not shown for transparent points for clarity. D: Log-log plots of terrace age and cumulative elevation change. Lines in B and D are power-law regressions. Note that zero on the y axis of A and C is set by the formation elevation of the first terrace, but this is merely for reference (relative elevation) and is not used in any calculations.

[1]GSA Data Repository item 2015217, methodological details and modeled and observed data, with Tables DR1–DR3 and Figures DR1 and DR2, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

and cumulative uplift (U_Σ):

$$U_\Sigma = z_t - z_{t0}, \tag{2}$$

where z_t and z_s are the elevations of the terrace and streambed, respectively, at time t, and z_{t0} is the formation elevation of the terrace (Figs. 1B and 1C). The time-averaged incision rate and uplift rate are calculated at each time step by dividing cumulative incision and cumulative uplift by the age of the terrace at time t (Fig. 1D).

From the perspective of the terrace, cumulative incision is unsteady and average incision rate is time dependent because the reference datum of the streambed is not fixed with respect to the geoid (Figs. 1C and 1D). The dependence of rate on measured interval persists at all time scales, but it disproportionately affects measurements calculated over shorter time intervals (Fig. 1D), an effect also predicted by an unrelated, physically based model (Hancock and Anderson, 2002, their figure 11).

EXPERIMENT TWO

This experiment assesses the impact of an assumed streambed elevation history on incision records derived from a terrace sequence. A series of 10 terraces generated at inflection points in our streambed elevation history range in age from ~480 k.y. to 60 k.y. (Fig. 2). The terraces are uplifted at a steady rate of 1 mm yr^{-1} and the final terrace elevations and ages are recorded and used for all subsequent calculations (Table DR1 in the Data Repository). The final terrace elevations are used to calculated cumulative incision using the correct dynamic streambed elevation history, as well as two static streambed elevations that are set at 25 m higher and 25 m lower than the mean elevation of terrace formation (~–11 m) (Fig. 2; Table DR1). The power-law relationship between cumulative incision and terrace age is determined for each assumed streambed elevation history to test for the fluvial Sadler effect (Fig. 2).

When the correct streambed elevation history is used to calculate cumulative incision, no fluvial Sadler effect is observed (Figs. 2A and 2B). This is a process analogous to how uplift rates are derived from marine terraces where sea-level curves are used to approximate a local base-level history (Lajoie, 1986; Merritts and Bull, 1989). However, it is generally not possible to reconstruct the full elevation history of a streambed, so most studies use the modern streambed elevation as a static datum for incision calculations. When a static channel elevation is assumed, a systematic bias is introduced into cumulative incision measurements that can produce the fluvial Sadler effect, by effectively adding or subtracting the elevation difference between the modern channel and the mean long-term base-level fall trend to each incision measurement (Figs. 2C and 2D). This bias skews data for younger, lower elevation terraces more so than for older, higher elevation terraces (Fig. 2; Fig. DR1); the degree of incision bias is proportional to the magnitude of offset between the static streambed datum and the mean formation elevation of terraces (Fig. DR2). When the modern channel elevation is lower than the mean elevation of terrace formation, the power-law exponent between cumulative incision and measured time interval (β) will be <1, whereas if the modern channel elevation is higher, β will be >1 (Figs. 2C and 2D; Fig. DR2). It is not surprising that many bedrock rivers yield a $\beta < 1$ (e.g., Finnegan et al., 2014), because rivers currently incising into bedrock have likely exceeded their mean trend in the Holocene, following a protracted period of little to no erosion during the late Pleistocene, when sediment flux was higher and sediment cover insulated the bed. In contrast, a $\beta > 1$ might occur when the modern channel position is elevated above the mean trend, as the case of systems undergoing aggradation or those in a transient state of adjustment after recent base-level fall.

When the average elevation of terrace formation is used to calculate incision, rate bias is minimized with $\beta \sim 1$ (Fig. DR2). Assuming that our conceptual model is correct, terraces form at similar elevations relative to the total range of streambed elevation variability. Therefore, avoiding use of the modern channel position and instead calculating incision with respect to other well-dated terraces will minimize rate bias imposed by the dynamic reference frame of rivers. Because Holocene terraces and valley bottoms are short-lived features in a landscape and potentially subject to significant bias, we suggest using Pleistocene terraces for such corrections. Another approach, given sufficient resources, is to date multiple terraces and regress through terrace age versus elevation data to derive a long-term incision rate (Pederson et al., 2006, 2013).

CORRECTIONS USING REAL WORLD EXAMPLES

Using a Monte Carlo error analysis to incorporate uncertainties associated with geochronology and elevation measurements, we compute the power-law relationship and associated 1σ standard error between cumulative incision and measured time interval with respect to the modern channel, as well as to the age and elevation of the lowest Pleistocene terrace for four incision records (Fig. 3; Tables DR2 and DR3; for full analysis description, see the Data Repository). The power-law exponent (β) of all incision records shifts toward unity when incision is calculated with respect to the lowest Pleistocene terrace, rather than the modern channel, and we suggest that these corrected records reflect largely unbiased long-term incision (Fig. 3). We argue that the remaining "bias" in the Musone River and Bidente River (northern Apennines, Italy) records reflects an actual change in the rate of tectonic uplift (Wegmann and Pazzaglia, 2009), whereas the Lee's Ferry (Arizona, USA) and Jemez River (New Mexico, USA) data sets that correct to $\beta \sim 1$ show steady base-level fall over the duration of the incision records (Pederson et al., 2013; Formento-Trigilio and Pazzaglia, 1998; Frankel and Pazzaglia, 2006).

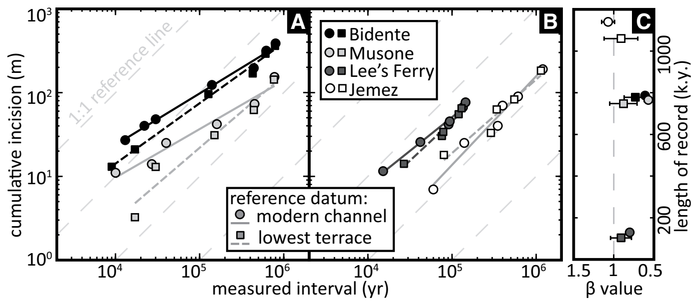

Figure 3. River incision records from Pleistocene terraces calculated relative to the static datum of the modern river channel (circles) and with respect to the lowest terrace (squares), a better approach. A: Results from the Bidente and Musone Rivers in the tectonically active northern Apennines, Italy (Wegmann and Pazzaglia, 2009). B: Data from less tectonically active settings of the Colorado River at Lee's Ferry (Arizona, USA) (Pederson et al., 2013) and the Jemez River (New Mexico, USA) (Formento-Trigilio and Pazzaglia, 1998; Frankel and Pazzaglia, 2006). β is power-law exponent (see text). C: β values and 1σ standard errors from power-law regressions through each data set.

DISCUSSION AND CONCLUSIONS

River erosion is an unsteady process disrupted by episodes of planation and aggradation. This unsteadiness results in the formation of terraces, but is also causes the streambed elevation to oscillate through time with respect to the geoid. Our modeling results and observations demonstrate that the fluvial Sadler effect may have little to do with the temporal distribution of hiatal intervals. Rather, the unappreciated effects of streambed elevation variability can systematically bias cumulative incision measurements, producing an apparent dependence of rate on measured time interval. The temporal nature of the forcing, whether stochastic, deterministic, or some combination, does not change our findings. Our results emphasize the need for broader consideration of reference frame mobility when interpreting geological measurements as a possible explanation for the Sadler effect. This is an important point considering the variety of techniques that are used to measure rates for the range of geological processes that exhibit the Sadler effect (Gardner et al., 1987).

We propose that most river incision records for which the modern streambed elevation was applied as a reference datum will exhibit the fluvial Sadler effect. This bias can be accounted for by calculating incision with respect to other well-dated terraces in the same sequence rather than the modern channel. Only after these corrections are applied to incision measurements can we begin to evaluate whether river incision records truly exhibit a systematic bias (cf. Finnegan et al., 2014). If such a bias is detected, it is important to keep in mind that long-term (>10^5 yr) changes in the rate of river erosion exist in nature, due to changes in the rate of tectonism and/or changes in climate-related erosional efficiency (e.g., Herman et al., 2013). It is also worth considering that an unintentional observational bias may exist for many studies of river incision because the locations that best preserve river terrace sequences are those in which erosion rates are accelerating. The results of this study indicate that records of river incision are largely unbiased and can serve as evidence of unsteadiness in rates of rock uplift and transient erosion when the dynamic reference frame of river channels is accounted for.

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REFERENCES CITED

Bull, W.B., 1991, Geomorphic responses to climatic change: New York, Oxford University Press, 326 p.

Finnegan, N.J., and Dietrich, W.E., 2011, Episodic bedrock strath terrace formation due to meander migration and cutoff: Geology, v. 39, p. 143–146, doi:10.1130/G31716.1.

Finnegan, N.J., Schumer, R., and Finnegan, S., 2014, A signature of transience in bedrock river incision rates over timescales of 10^4–10^7 years: Nature, v. 505, p. 391–394, doi:10.1038/nature12913.

Formento-Trigilio, M.L., and Pazzaglia, F.J., 1998, Tectonic geomorphology of the Sierra Nacimiento: Traditional and new techniques in assessing long-term landscape evolution in the southern Rocky Mountains: Journal of Geology, v. 106, p. 433–454, doi:10.1086/516034.

Frankel, K.L., and Pazzaglia, F.J., 2006, Mountain fronts, base-level fall, and landscape evolution: Insights from the southern Rocky Mountains, *in* Willett, S.D., et al., eds., Tectonics, climate, and landscape evolution: Geological Society of America Special Paper 398, p. 419–434, doi:10.1130/2006.2398(26).

Gardner, T.W., Jorgensen, D.W., Shuman, C., and Lemieux, C.R., 1987, Geomorphic and tectonic process rates: Effects of measured time interval: Geology, v. 15, p. 259–261, doi:10.1130/0091-7613(1987)15<259:GATPRE>2.0.CO;2.

Hancock, G.S., and Anderson, R.S., 2002, Numerical modeling of fluvial strath-terrace formation in response to oscillating climate: Geological Society of America Bulletin, v. 114, p. 1131–1142, doi:10.1130/0016-7606(2002)114<1131:nmofst>2.0.co;2.

Herman, F., Seward, D., Valla, P.G., Carter, A., Kohn, B., Willett, S.D., and Ehlers, T.A., 2013, Worldwide acceleration of mountain erosion under a cooling climate: Nature, v. 504, p. 423–426, doi:10.1038/nature12877.

Howard, A.D., Dietrich, W.E., and Seidl, M.A., 1994, Modeling fluvial erosion on regional to continental scales: Journal of Geophysical Research, v. 99, p. 13,971–13,986, doi:10.1029/94JB00744.

Jerolmack, D.J., and Paola, C., 2010, Shredding of environmental signals by sediment transport: Geophysical Research Letters, v. 37, L19401, doi:10.1029/2010GL044638.

Korup, O., 2006, Rock-slope failure and the river long profile: Geology, v. 34, p. 45–48, doi:10.1130/G21959.1.

Lajoie, K.R., 1986, Coastal tectonics, *in* Wallace, R., ed., Active tectonics: Studies in Geophysics: Washington, D.C., National Academy Press, p. 95–124.

McPhillips, D., Bierman, P.R., and Rood, D.H., 2014, Millennial-scale record of landslides in the Andes consistent with earthquake trigger: Nature Geoscience, v. 7, p. 925–930, doi:10.1038/ngeo2278.

Merritts, D., and Bull, W.B., 1989, Interpreting Quaternary uplift rates at the Mendocino triple junction, northern California, from uplifted marine terraces: Geology, v. 17, p. 1020–1024, doi:10.1130/0091-7613(1989)017<1020:IQURAT>2.3.CO;2.

Merritts, D., and Vincent, K.R., 1989, Geomorphic response of coastal streams to low, intermediate, and high rates of uplift, Medocino triple junction region, northern California: Geological Society of America Bulletin, v. 101, p. 1373–1388, doi:10.1130/0016-7606(1989)101<1373:GROCST>2.3.CO;2.

Mills, H.H., 2000, Apparent increasing rates of stream incision in the eastern United States during the late Cenozoic: Geology, v. 28, p. 955–957, doi:10.1130/0091-7613(2000)28<955:AIROSI>2.0.CO;2.

Pazzaglia, F.J., 2013, Fluvial terraces, *in* Shroder, J.F., ed., Treatise on geomorphology Volume 9: Fluvial geomorphology: San Diego, Academic Press, p. 379–412, doi:10.1016/B978-0-12-374739-6.00248-7.

Pazzaglia, F.J., and Brandon, M.T., 2001, A fluvial record of long-term steady-state uplift and erosion across the Cascadia forearc high, western Washington state: American Journal of Science, v. 301, p. 385–431, doi:10.2475/ajs.301.4-5.385.

Pederson, J.L., Anders, M.D., Rittenhour, T.M., Sharp, W.D., Gosse, J.C., and Karlstrom, K.E., 2006, Using fill terraces to understand incision rates and evolution of the Colorado River in eastern Grand Canyon, Arizona: Journal of Geophysical Research, v. 111, F02003, doi:10.1029/2004JF000201.

Pederson, J.L., Cragun, W.S., Hidy, A.J., Rittenour, T.M., and Gosse, J.C., 2013, Colorado River chronostratigraphy at Lee's Ferry, Arizona, and the Colorado Plateau bull's-eye of incision: Geology, v. 41, p. 427–430, doi:10.1130/G34051.1.

Sadler, P.M., 1981, Sediment accumulation rates and the completeness of stratigraphic sections: Journal of Geology, v. 89, p. 569–584, doi:10.1086/628623.

Schumer, R., and Jerolmack, D.J., 2009, Real and apparent changes in sediment deposition rates through time: Journal of Geophysical Research, v. 114, F00A06, doi:10.1029/2009JF001266.

Snyder, N.P., Whipple, K.X., Tucker, G.E., and Merritts, D.J., 2000, Landscape response to tectonic forcing: Digital elevation model analysis of stream profiles in the Mendocino triple junction region, northern California: Geological Society of America Bulletin, v. 112, p. 1250–1263, doi:10.1130/0016-7606(2000)112<1250:LRTTFD>2.0.CO;2.

Wegmann, K.W., and Pazzaglia, F.J., 2002, Holocene strath terraces, climate change, and active tectonics: The Clearwater River basin, Olympic Peninsula, Washington State: Geological Society of America Bulletin, v. 114, p. 731–744, doi:10.1130/0016-7606(2002)114<0731:HSTCCA>2.0.CO;2.

Wegmann, K.W., and Pazzaglia, F.J., 2009, Late Quaternary fluvial terraces of the Romagna and Marche Apennines, Italy: Climatic, lithologic, and tectonic controls on terrace genesis in an active orogen: Quaternary Science Reviews, v. 28, p. 137–165, doi:10.1016/j.quascirev.2008.10.006.

Whipple, K.X, 2004, Bedrock rivers and the geomorphology of active orogens: Annual Review of Earth and Planetary Sciences, v. 32, p. 151–185, doi:10.1146/annurev.earth.32.101802.120356.

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