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Invited review

Multiple paths to straths: A review and reassessment of terrace genesis

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ABSTRACT

Strath terraces, an important tool in tectonic geomorphology, have been attributed to climatic, tectonic, volcanic, and human activity, yet the pathways connecting external forcings to the channel response leading to terrace formation are highly variable and complex. To better understand variability and controls on the pathways between forcing and terrace formation, we created a comprehensive database of 421 strath terraces from peer-reviewed literature and noted the strath age and rock type, the ascribed forcing (climate, tectonics, volcanoes, or humans) or whether the cause was unascribed, and the pathway between forcing and strath incision or planation. Study authors identify climate, tectonics, volcanoes, and humans as the forcing for 232 (55%), 20 (5%), 8 (2%), and 5 (1%) strath terraces in our compilation respectively. A forcing was not identified for the remaining 156 (37%) terraces. Strath terraces were dated using 14 different methods: 71% of terraces in our database are dated using methods, such as radiocarbon and optically stimulated luminescence, that date planation and give a maximum age of incision; 16% of terraces are dated with methods that give a minimum age of incision; and 14% use a variety of methods for which a generalization about incision age cannot be made. That the majority of terrace studies use planation ages to understand terrace formation highlights the necessity of knowing the relative timescales of incisional and planation phases, which has so far been quantified in only a handful of studies. In general, rivers in arid regions plane straths in interglacial periods when discharge and sediment transport capacity increase, whereas temperate rivers plane in glacial or interglacial periods when sediment supply increases. Heterogeneities in rock strength between watersheds further control how sediment is produced and when straths are planed. Globally, these regional and watershed controls result in strath planation and incision during all parts of the glacial cycle. Terraces with no identified forcing in our database reach a maximum frequency during the late Holocene (4 kya–present) and could potentially be explained by regional deforestation and increased anthropogenic fire frequency, regionally active tectonics, and climate fluctuations. Deforestation and fires, by reducing the supply of wood to streams, decrease instream sediment retention and could convert alluvial channels to bedrock, thus promoting strath incision. The regional and watershed controls on strath formation highlighted in our database, as well as the possibility of anthropogenic forcings on strath terrace formation in the late Holocene, illustrate the importance of explicitly establishing the pathway between forcing and strath terrace formation in order to accurately interpret the cause of strath formation.

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1. Introduction

Strath terraces are important geomorphic markers of tectonic strain, yet, to date, few meta-analyses have been conducted on the cause and timing of strath formation (e.g., Montgomery, 2004; Pazzaglia, 2013). Strath terraces form as a result of two fluvial processes: lateral planation, which bevels the strath, and vertical incision, which abandons the strath as a terrace (Fig. 1). Incision and planation of strath terraces are caused by adjustments to the river slope, sediment supply and caliber, and water discharge, all of which affect the transport of sediment. Lateral beveling is often associated with increased sediment loads (e.g., Bull, 1990; Personius et al., 1993; Hancock and Anderson, 2002; Wegmann and Pazzaglia, 2002). Higher sediment loads protect the underlying bedrock from vertical incision (Sklar and Dietrich, 2001) and can promote a wider, braided morphology that enhances bedrock bank erosion through subaerial weathering (e.g., Montgomery, 2004; Finnegan and Balco, 2013). Lateral planation can also occur rapidly through subaerial bedrock weathering and erosion once low surfaces are stripped of alluvium during high magnitude flows (Collins et al., 2016) and through lateral migration of meandering channels (Merritts et al., 1994; Limaye and Lamb, 2016). Strath incision typically occurs when the transport capacity exceeds sediment supply, thereby exposing underlying bedrock to vertical erosion.

External forcings of strath terraces can be grouped into four broad categories: climate (e.g., Pan et al., 2003; Amos et al., 2007; Wegmann and Pazzaglia, 2009); tectonics (e.g., Harkins et al., 2005); volcanic activity (e.g., Ely et al., 2012; Baynes et al., 2015); and human action (e.g., Lewin et al., 1991; Carcaillet et al., 2009; Molin et al., 2012) (Fig. 2). Each of these forcings can cause lateral planation or vertical incision; however, all require that the landscape is undergoing a base level change, typically driven by steady rock uplift, to accommodate incision and allow terrace preservation. Global glacial cycles are the most common climatic phenomenon linked to strath terrace formation. Previous studies have related strath planation during interglacial periods (Van der Woerd et al., 1998; Fuller et al., 2009; Lewis et al., 2009) and glacial periods (Amos et al., 2007; Wegmann and Pazzaglia, 2009; Wang et al., 2015). That planation can occur in both parts of the cycle implies that fluvial response to glaciation, and perhaps other landscape perturbations, may be modulated by intermediary, regional-scale environmental variables. Additionally, the commonly held assumption that climate drives strath terrace formation in the majority of cases (e.g., Hancock and Anderson, 2002; Pan et al., 2003; Pazzaglia, 2013) has never, to our knowledge, been tested against a full data set of studied strath terraces.

With the increasing use of strath terraces in geomorphological studies, the large data set of strath ages and associated forcings now at hand allows us to reevaluate prevailing geomorphic theory on strath formation against the collected data. Here, we use an expansive compilation of previous work on strath terraces to analyze how many terraces are attributed to each forcing and the various pathways between forcing

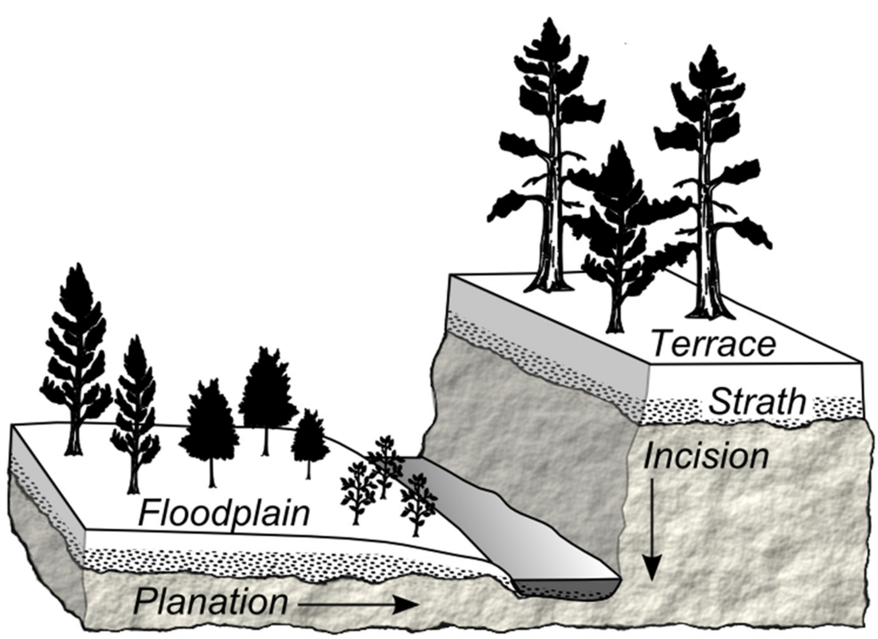

Fig. 1. Illustration of the relationship between the bedrock strath and the terrace, as well as definitions of incision and planation directions. Succession of young alders (*Alnus rubra*) to older pines (*Pinus ponderosa*) on the floodplain indicates planation direction, as indicated by the arrow. Stipling represents gravel to cobble size alluvium, while white shading are floodplain sediments, generally sand to clay sized. Bedrock is shown by the rough texture.

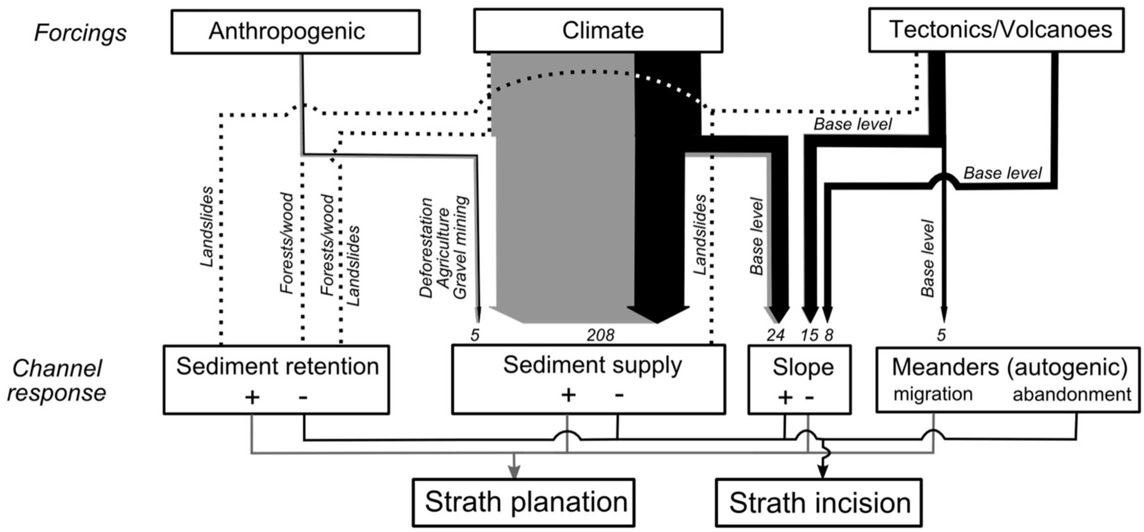

Fig. 2. External forcings enact channel response through a variety of pathways, eventually leading to incision or planation of a strath. The line thickness of pathways between forcings and channel responses represent the number of strath terraces in our database attributed to that pathway, with the total above the associated channel response. Black lines represent strath terraces that had independent evidence for the ascribed forcings, while gray lines indicate that only strath age was used to assign the forcing. Dashed lines are hypothesized pathways between forcings and stream variables, as discussed in the text. Climate enacts a sediment supply response in numerous ways, which include changes in the rate of mechanical and chemical weathering, landsliding, glacial erosion, and fluvial erosion and transport (see Section 3.1.1 for details).

and strath formation, as well as whether terraces lacking an identified forcing can be attributed to a forcing based on their geologic history. To better interpret reported strath terrace ages, we identify the methods used to date terraces and discuss the constraints those methods place on the timing of terrace formation. We find that climate forcings are modulated by regional climate and watershed-scale characteristics, such as rock type and glacial proximity, which exert local controls on the timing and nature of fluvial response to glacial cycles. Although glacial cycles are reportedly responsible for the majority of mapped and dated strath terraces, over one-third of the terraces in our database were not associated with an identified forcing. We evaluate possible controls on late Holocene terraces, including the potential role of human-caused changes to forest structure, in-stream wood abundance, and fire regimes that affect sediment retention and river incision.

2. Database compilation

To better understand how and when strath terraces form in response to climatic, tectonic, volcanic, and anthropogenic forcings, we compiled an exhaustive database of dated strath terraces from peer-reviewed publications and analyzed the reported controls on river incision and strath planation. We did not include in our compilation strath terraces lacking an age control, even if terrace formation was discussed. Using search engines and previous compilations of strath terraces (e.g., Montgomery, 2004; Finnegan et al., 2014), we gathered data for 421 dated strath terraces from 78 studies (see Supplementary material Table S1). We noted the strath age, dating method, whether the age sample was collected from within terrace materials or from the terrace surface, and whether the age represents strath planation or strath incision. Ages presented in this compilation are all in calendar years before present. For terraces that were dated multiple times, we chose the age that is closest to when the strath was incised. For example, in a suite of radiocarbon ages wherein each age represents the deposition of the dated material when the strath was an active surface, the youngest age is taken as the best estimate of the end of strath planation and beginning of strath incision. We also noted the strath terrace location, strath lithology, and the forcing mechanism attributed to strath planation and incision.

To recognize how well supported the ascribed forcing is, we noted whether each terrace had independent evidence linking strath incision or planation to the identified forcing. Independent evidence used to locally relate strath formation to a forcing included morphologic, palynologic, or isotopic data. Strath terraces lacking independent evidence were those to which a forcing was attributed based solely on age correlation.

For terraces attributed to climate, we noted whether the terrace was attributed to marine isotope stage (MIS) glacial cycles or to shorter-term climatic fluctuations. If study authors related the terrace to MIS glaciations, then we additionally noted when planation and incision occurred within the glacial cycle. To examine whether volcanism, tectonics, climate, or human actions can account for Holocene strath terraces that currently lack an identified forcing, we used data sets of active volcanoes (Smithsonian Institution, 2013), peak ground acceleration (Giardini et al., 1999), and glacial maximum ice extent (Ehlers et al., 2011), and literature reviews on Holocene climate fluctuations and deforestation age (see Table S1 for site-specific references) to compare against terrace location and age.

3. Results

3.1. Causes of strath formation

Of the 421 strath terraces in our compilation, 232 (55%) were attributed to climate, 20 (5%) to tectonics, 8 (2%) to volcanoes, 5 (1%) to anthropogenic activity, and 156 (37%) lacked an identified forcing (Figs. 2 and 3). Comparing forcing mechanism against the original study date showed no discernable bias in attributed forcing mechanism with time (Supplementary Fig. S1). Fig. 2 shows the pathways between each external forcing and the channel response that led to strath planation and incision. The arrows connecting forcings to channel response represent the pathways taken by the 265 strath terraces in our database that were ascribed to a forcing, with thickness of arrows showing the proportion of terraces and black or gray color indicating whether the path between forcing and channel response had or lacked independent evidence for the forcing respectively.

Of the 265 strath terraces that were assigned a forcing, under half ($n = 103$) had independent evidence of the assigned forcing. Nearly all (98%) of the terraces lacking evidence were from strath terraces attributed to climate (Figs. 2 and 4). All terraces ascribed to volcanic forcings had independent evidence linking strath formation to volcanic forcings; however, these terraces are from a single study (Baynes et al., 2015). Anthropogenic strath terraces are almost evenly split between having and lacking independent evidence but come from only four studies (Lewin et al., 1991; Carcaillet et al., 2009; Wegmann and Pazzaglia, 2009; Molin et al., 2012). Strath terraces attributed to tectonic activity, from only seven studies (Table S1), were mostly ascribed to a forcing with independent evidence, but whether this is because it is easier to find supporting evidence of tectonic forcings or if this finding reflects the small sample size is unclear. Forty-seven studies include climatic strath terraces, and 68% of those terraces were attributed to a forcing based on age correlation alone. The greater number of studies involved, which include 232 sets of strath terraces, suggest that the high proportion of climate strath terraces lacking independent evidence of climate forcing is not caused by a skewed sample size. Rather it may be reflective of whether such evidence was available and within the scope and budget of the study.

In the following sections, we review how these four forcings influence channel response and lead to strath planation and incision. We draw from studies that used terrace age and independent secondary evidence to assign a forcing because these studies, in general, were more likely to describe the pathways and channel response between forcing and terrace formation. As indicated by Fig. 2, multiple pathways connect each forcing to strath terrace formation.

3.1.1. Climate

Strath planation is attributed most frequently to increased sediment supply during the transition from glacial to interglacial periods ($n = 31$) and during glacial periods ($n = 81$) (Figs. 2 and 5). In the nonglaciated Oregon Coast Range, Personius et al. (1993) used a suite of radiocarbon ages to determine that strath planation occurred during the glacial to interglacial transition. Concurrently increased landsliding in the central Coast Range, driven by early Holocene increased storminess, was dated by Reneau et al. (1990) and likely led to the stream aggradation and strath planation documented by Personius et al. (1993). In the Bhagirathi Valley, Himalaya, cosmogenic exposure ages of strath terraces are similar to optically stimulated luminescence (OSL) ages of glacial sediment, implying that remobilization of glacial debris caused strath planation in glacial to interglacial transitions (Barnard et al., 2004). However, glacial debris in New Zealand and Italy was found to be transported earlier in the glacial cycle, causing strath planation to occur within the full glacial period (e.g., Formento-Trigilio et al., 2003; Picotti and Pazzaglia, 2008). In the nonglaciated South Fork Eel River, California, OSL dates on terraces and pollen lake records show strath planation occurred during a wet interglacial period (Fuller et al., 2009). The wetter period likely led to more landsliding and sediment delivery to the river, leading to strath planation (Fuller et al., 2009).

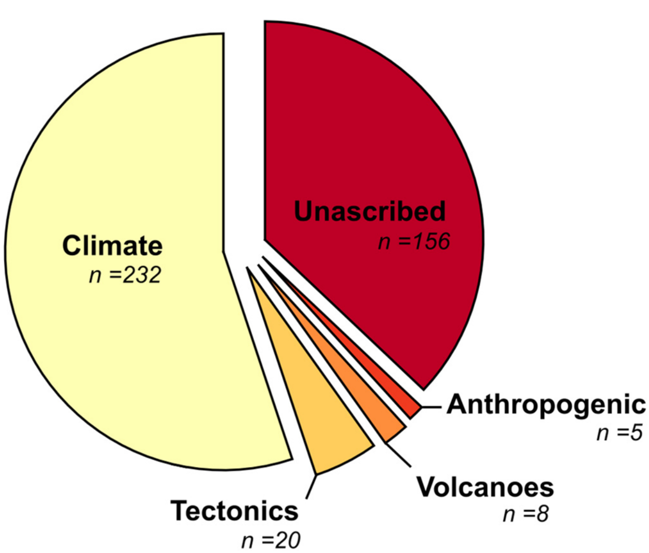

Fig. 3. The distribution of external forcings attributed to strath formation. Numbers represent the total number of terraces in our database attributed to each forcing.

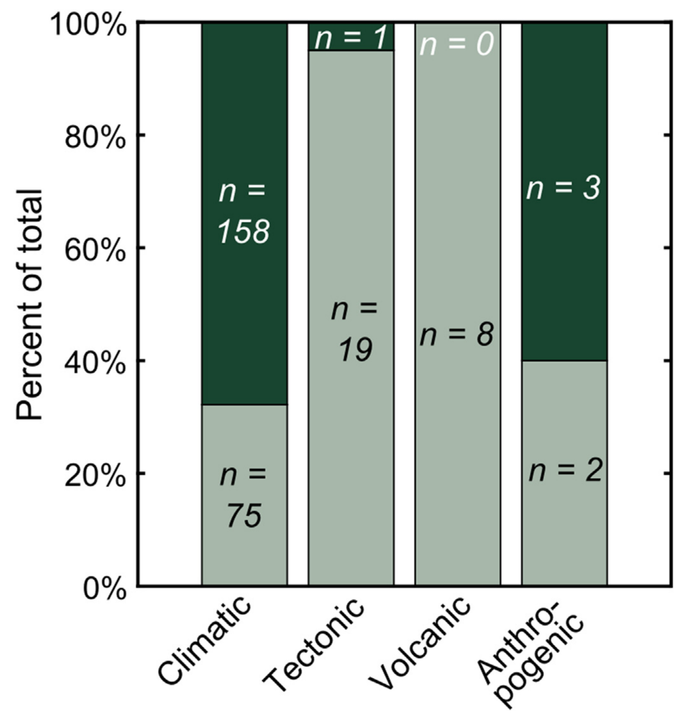

Fig. 4. The proportion of strath terraces having (light green) and lacking (dark green) independent evidence of the assigned forcing. See Methods for definitions and examples of independent evidence.

Taken together, these studies demonstrate that the timing of strath planation varies with the timing of increased sediment supply which, in turn, depends on precipitation and vegetation patterns in nonglaciated basins (Personius et al., 1993; Fuller et al., 2009) and the mobilization of glacial debris in glaciated basins (Formento-Trigilio et al., 2003; Barnard et al., 2004; Picotti and Pazzaglia, 2008).

Fewer studies have described strath incision during glacial cycles, and from these studies, no generalizable path is evident between MIS forcing and channel response leading to incision. While the timing of strath incision cannot be dated directly, the timing of incision can be constrained using the oldest age obtained from the next lowest terrace, giving a minimum estimate of incision time. This age, in combination with the youngest planation age of the strath terrace of interest, provides a maximum bound of the terrace formation timing. In such a

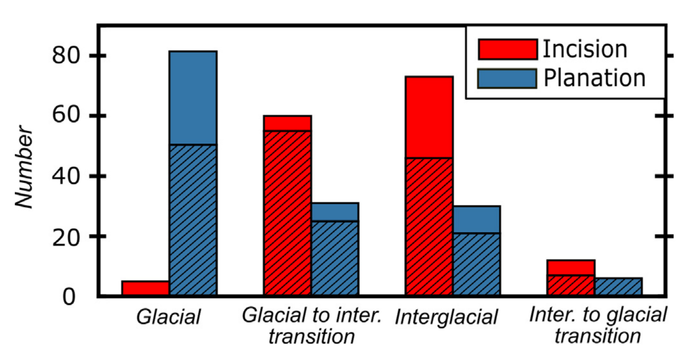

Fig. 5. Timing of strath incision (red) and planation (blue) in response to global climate, subdivided into glacial periods, glacial to interglacial transitions, interglacials, and interglacial to glacial transitions. Strath terraces located in temperate regions are shown by the hatched bars, while arid regions are shown as plain bars.

manner, incision in the Oregon Coast Range was estimated to occur in the Holocene interglacial, after revegetation decreased the sediment supplied from hillslopes (Personius, 1995). In the Somme and Seine rivers, France, Antoine et al. (2000) used palynological and sedimentological data to infer that stream discharge increased during interglacial to glacial transitions but that cohesive hillslope vegetation limited the colluvial sediment input. Sediment supply remained low while transport capacity increased, enabling river incision and strath terrace formation during the transition to glacial periods (Antoine et al., 2000).

Incision can also be driven by an increase in river slope caused by climate-induced base level fall. Draining of Glacial Lake Agassiz during deglaciation decreased base level and formed a knickpoint at the mouth of the Le Sueur River, Minnesota (Gran et al., 2013). This knickpoint propagated upstream, creating strath terraces from 13 to 1.5 kya.

In examples from Taiwan and the Himalaya, straths were planed during periods of increased sediment supply caused by monsoon strength. In Taiwan, aggradation and planation of two sets of strath terraces was correlated with periods of intensified storm activity in the middle and late Holocene (Hsieh and Knuepfer, 2001). Periodic storms increased sediment delivery from hillslopes above the transport capacity, causing fluvial aggradation and strath planation. Then, rivers incised during an intervening cold and dry period in the middle Holocene owing to reduced sediment supply. In the Himalaya, Kothyari et al. (2016) found strath planation corresponded with a strengthened Indian summer monsoon. However, even within neighboring drainages, rivers responded asynchronously, and only one of the two rivers studied planed a strath during early Holocene monsoon intensification (Kothyari et al., 2016).

Early Holocene warming at ~12.7–12.5 and 10 kya initiated an extended period of strath planation in the Tibetan Plateau (Haibing et al., 2005; Mériaux et al., 2005). The warmer and wetter climate during these times increased sediment supply, which led to increased lateral river erosion and planation. After the early Holocene warm period, sediment supply was reduced and river incision initiated. In northeastern Tibet, late Holocene strath terraces were created by punctuated river incision during warm intervals in an arid climate (Van der Woerd et al., 1998). Although the cause of strath planation could not be identified, cosmogenic exposure ages on the terrace surface indicate planation was coincident with early Holocene summer monsoon extension into NE Tibet. The summer monsoons would have transported sediment from the hillslopes into the channel, increasing the sediment cover and lateral mobility and planing a strath.

3.1.2. Tectonics

Tectonic activity leads to strath terrace formation through changes to base level induced by uplift and subsidence (Fig. 2). An increase in rock uplift rate over time will increase the river slope, driving regional incision and strath abandonment (e.g., Van der Woerd et al., 2001; Cheng et al., 2002) (Fig. 2). Pazzaglia (2013) noted, based on previous literature, that strath terraces formed from changes in rock uplift rate are more likely to be preserved in slowly deforming regions (e.g., Van Balen et al., 2000; Meyer and Stets, 2002; Gibbard and Lewin, 2009). Fault offset is a spatially discrete tectonic control on base level in which the river crosses the fault scarp and incision or planation may be promoted, depending on the sense of fault slip. For example, Harkins et al. (2005) dated a series of Holocene strath terraces resulting from periodic normal fault slip and slope adjustment along Big Sheep Creek, Montana, wherein the knickpoint originating from the fault scarp propagated upstream and abandoned strath terraces several kilometers upstream of the fault.

Tectonic uplift also contributes to autogenic terrace formation by providing a constant base level drop to sustain long-term incision (Fig. 2). Autogenic strath terraces form in meandering bedrock rivers from the combination of meander migration, steady incision, and meander cutoffs as described in Oregon and California (Merritts et al., 1994; Finnegan and Dietrich, 2011). In Oregon, the Smith River, confined within a narrow bedrock valley, formed strath terraces through the pinch-out of meanders, in which case the strath is the former riverbed (Finnegan and Dietrich, 2011). Along the Mattole River, California, where the river was able to meander across a wide valley, steady incision resulted in relative uplift of old meander belts and the formation of strath terraces (Merritts et al., 1994). Numerical simulations by Limaye and Lamb (2016) were able to form strath terraces by imposing a steady base level drop on a continuously meandering river, which formed terraces similar in geometry to those on the Mattole River. In these case studies, incision was driven by gradual tectonic uplift of the landscape relative to sea level. Sediment and water supply did not need to change for terrace incision and planation to occur.

3.1.3. Volcanoes

Changes to river slope induced by volcanic activity have led to strath incision (Baynes et al., 2015) and planation (Ely et al., 2012) (Fig. 2). In Iceland, volcanic eruptions near glaciers caused rapid melt and catastrophic flooding that rapidly eroded bedrock and formed knickpoints. Over time, upstream propagation of the knickpoint abandoned straths, creating terraces (Baynes et al., 2015). In this case, terrace planation was not explicitly addressed but was likely owing to preferential erosion along planar lava flow boundaries. The disruption and physical damming of rivers by lava flows can also determine whether rivers incise or plane; In eastern Oregon, Ely et al. (2012) used the age of lava flows and cosmogenic exposure ages of eroded surfaces to determine that lava dams could induce strath terrace planation and incision. Lava dams along the Owyhee River blocked or diverted water flow, lowering the upstream slope. As a result, the river upstream aggraded and widened, and incision rates slowed because of the development of an alluvial cover. Once aggradation reached the lava dam top, the bedload abraded the lava flow and rapidly incised at rates of ~1.8 mm/y. Periodic lava dams created cycles of planation and incision, documented by the presence of narrow strath terraces carved into the flows (Ely et al., 2012).

3.1.4. Human activity

In the last few thousand years, changes to sediment supply by human activity (e.g., Syvitski and Kettner, 2011) have been documented to drive planation and incision of strath terraces (Fig. 2). Two strath terraces in Albania and Greece were planed <1 kya in response to increased sediment from logging and farming, with incision of the strath occurring when the sediment supply lowered post-disturbance (Lewin et al., 1991; Carcaillet et al., 2009). Late Holocene (3.5–1.5 kya) strath terraces in Italy and Romania likely were incised in response to instream gravel mining, although whether incision was caused by mining-induced changes to slope or sediment supply was not clear (Wegmann and Pazzaglia, 2009; Molin et al., 2012).

In Washington State, USA, century-old strath terraces in the Teanaway and Willapa rivers formed coincident with anthropogenic deforestation, log drives, and the presumed resulting loss of instream wood (Collins et al., 2016; Schanz and Montgomery, 2016) (dashed lines in Fig. 2). Logging in these regions at the end of the nineteenth century and beginning of the twentieth century reduced the amount and size of wood in rivers and the supply of wood from riparian forests (Montgomery et al., 2003). Large wood in rivers can cause sediment deposition through the creation of eddies (Abbe and Montgomery, 1996) and jams that physically block sediment transport and increase sediment retention (Montgomery et al., 1996). As a result of the increased sediment retention from large wood, bedrock-floored channels can be converted to alluvial channels. Similarly, the removal of wood can convert a formerly alluvial channel to a bedrock channel (Montgomery et al., 1996; Massong and Montgomery, 2000; Faustini and Jones, 2003). Thus, the loss of large wood through logging, as well as the reduced size of wood from short-rotation forestry, can potentially decrease sediment retention and may convert alluvial channels to bedrock, thereby opening the channel to incision. Collins et al. (2016) and Schanz and Montgomery (2016) noted that artificial dam-burst floods, used to transport timber downstream, and slaking-prone bedrock likely enhanced incision rates in their study regions, leading to discernable strath terrace formation within a century.

3.2. Constraining strath terrace age

To understand what a single strath terrace age represents and to recognize how to compare terrace ages regionally and globally, we examine the different age methods and sample locations used to date terraces in the database. Strath terraces in our database were dated using 14 different methods (Table 1). Samples for dating analyses were collected from the alluvium overlying the strath but below the terrace surface, from loess deposits and exposed cobbles that mantle the terrace surface, or from the top of the bedrock strath. In general, ages derived from samples collected within the buried alluvium that overlies the strath represent when the strath was an active surface and provide maximum age constraints on strath incision and terrace formation. Dating soils and loess deposits from the terrace top gives a minimum age of strath incision, as the soil and loess could not have accumulated until after the surface was abandoned. Similarly, exposed cobbles on the terrace surface, dated using cosmogenic exposure, also provide minimum ages of strath incision because the exposure of the cobble to cosmic rays could not occur until the surface was inactive. Bedrock samples taken directly from the exposed strath, dated for exposure to cosmogenic rays, record the time since the strath was created and thus represent a maximum age constraint on incision.

Conversely, when considering the planation age of the strath rather than the incision age, material that formed or deposited once the terrace surface stabilized, such as soils, loess, and exposed cobbles, provide minimum ages of planation. Ages from bedload deposits on top of the bedrock strath, deposited while the strath was planed, provide the best estimate of planation age. Overbank floodplain sediment on top of the strath could either be deposited when the strath was planed or during incision into the strath, making it hard to interpret a date from such deposits. Cosmogenic exposure ages of the bedrock strath can also date the strath planation, assuming that no additional erosion occurred after the strath was originally planed.

The majority of strath terraces are dated using material from locations that give a maximum age of strath incision. Thirty percent of strath terraces were dated using radiocarbon found within the alluvial sands and cobbles that overly the strath (Table 1); this dates the deposition of the material while the strath was an active surface. The second most common method, accounting for 22% of the total, is OSL on fluvial sands in the terrace and also constrains the maximum age of incision. In contrast, the third most common method, representing 8% of our database, is cosmogenic nuclides on terrace surface deposits that dates material that may have become exposed after the terrace was abandoned, thus providing a minimum date of terrace incision. Overall, 71% of the terrace ages in our database are of material from the terrace alluvium or the bedrock strath and are maximum ages of incision. Sixteen percent of terrace ages are from terrace surface material and represent a minimum incision age. The remaining 13% are dated using relative age methods such as slip rate, stratigraphy, or MIS correlation or were dated using multiple methods with different sample locations, and so whether the ages represent a minimum or maximum estimate of terrace incision must be evaluated for each terrace.

Recognizing that the terrace age dates strath planation for most terraces in our database has important implications for interpreting strath formation. Several studies have found that planation phases are much longer than incisional phases and span 10 ky at least (Wegmann and Pazzaglia, 2002; Collins et al., 2016; Schanz and Montgomery, 2016). Consequently, using a planation age to constrain the environmental forcing responsible for incision can result in substantial uncertainty in how closely the planation age approximates the onset of incision. If strath terrace formation is attributed to a forcing based on similar timing between age constraint and a known climatic, tectonic, volcanic, or anthropogenic event—as is done for 61% of terraces in our database—then the strength of the attribution depends on the original age constraint. The forcing responsible for incision is likely not well constrained if only a planation age is available; a more robust attribution would rely on either an incision age or on an estimated incision age derived from planation ages of two bounding sets of strath terraces.

Table 1
Strath dating methods.

	Material location		
	In terrace alluvium	Terrace surface: loess, cobbles	Top of bedrock strath
Radiocarbon	128	11	
Cosmogenic nuclides	11	32	30
Optically stimulated luminescence	93	11	
Thermal luminescence	5	5	
Paleomagnetism	2	4	
Magnetostratigraphy	4	4	
Electron Spin Resonance	13	2	
IRSL	3		
U/Th	10		
Methods w/o material location			Material location N/A
Previous literature reviews			12
Slip rate			2
Stratigraphic relationship			6
Paleosol correlation			1
MIS correlation			1
Multiple methods			31

3.3. Timing of strath terrace formation

Strath terrace ages in our compilation range from 2.9 Mya to 0.03 kya but are concentrated in the Holocene and late Pleistocene (Fig. 6). When terrace age is binned by 0.5 kya, the most frequent period of strath formation is 2–2.5 kya, though a generalized peak in terrace formation occurs during the late Holocene from 4 kya to present (Fig. 6B). The age distribution of terrace formation also exhibits local maxima during the middle Holocene, from ~5–6.5 kya, and in the early Holocene from 11 to 11.5 kya.

All four forcings—climate, tectonics, volcanoes, and human action—formed strath terraces in the Holocene, but the relative frequency of each forcing varies. Tectonic terraces are not common but are evenly spread throughout the Holocene, whereas terraces attributed to volcanic activity are infrequent but cluster near the time of volcanism and associated river incision (Baynes et al., 2015). The five terraces identified as caused by anthropogenic forcings all date to after 4.5 kya. Climate is the attributed cause of most terraces in the early Holocene, but the relative frequency of climate-induced strath terraces decreases toward the present day. Instead, although the number of terraces reaches a peak in the late Holocene from 4 kya to present, terraces formed because of climate become less frequent and terraces without an identified forcing make up the majority. In Section 4.2, we discuss possible causes of late Holocene terrace formation.

4. Discussion

4.1. Global, regional, and watershed controls on terrace formation

Our results show that a number of general pathways exist between forcing and strath terrace formation (Fig. 2) and that these pathways, especially for climate forcings, are modified by global, regional, and watershed-scale characteristics that individualize river response. Bull (1990) recognized that global climate has variable impacts on the landscape when he observed that regional climate zones controlled the

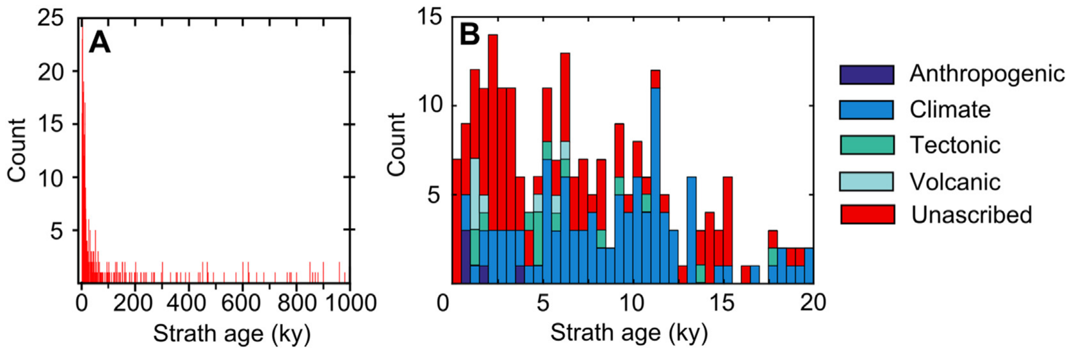

Fig. 6. (A) Age distribution of strath terraces in our database over the last million years. Age is binned by 1 ky. (B) Age distribution for the last 20 ky in 0.5 ky bins and colored by the ascribed forcing.

timing of aggradation, with rivers in humid and mesic climates aggrading in full glacial periods while arid rivers aggraded in interglacial periods. Moreover, rivers within each climate zone recorded different numbers of aggradation events based on watershed lithology and vegetation. The strath terraces documented by decades of research since Bull's (1990) findings make it possible to elaborate on how regional and watershed controls interact with global climate forcings on strath terrace formation.

Global-scale MIS climatic variations are often modulated by regional climate patterns, which affect when sediment is produced and transported, thus controlling when straths are planed and incised. In the arid Gobi-Altay range, Mongolia, Vassallo et al. (2007) used cosmogenic exposure ages on terraces and alluvial fans to determine that strath planation occurred during wet interglacial periods when sediment produced in the glacial period was mobilized. In this case, the stream system is transport-limited through most of the glacial cycle. In contrast, rivers in temperate climates appear to be supply-limited during the majority of the glacial cycle, and straths are planed when sediment supply increases in association with MIS variations. In New Zealand, sparse vegetation, indicated by terrace stratigraphy and climate proxy data in the Huangarua River, allowed high hillslope run-off, thereby increasing sediment supply and causing channel braiding and strath planation (Formento-Trigilio et al., 2003). However, strath planation can also occur in interglacial periods in temperate climates. Optically stimulated luminescence (OSL) ages of strath terraces along the South Fork Eel River, California, show strath planation in a temperate climate occurred during interglacial periods, caused by increased sediment supply from precipitation-driven landsliding (Fuller et al., 2009). In the Oregon Coast Range to the north, radiocarbon dates of strath terraces and colluvial hollows also show a temporal correlation between increased landsliding and strath planation in interglacial periods (Personius, 1995). Although these latter two examples support that rivers in temperate climates tend to be supply limited, the timing of increased sediment supply in response to MIS glaciation differs from that found by Formento-Trigilio et al. (2003) and may be indicative of watershed-scale controls on sediment supply.

At the watershed-scale, characteristics such as rock type and glacial proximity further modulate the influence of global climate change on strath terrace formation. In the Musone and Bidente rivers, Italy, radiocarbon ages of strath terraces formed in the two adjoining basins reveal asynchronous strath planation caused by lithologic differences (Wegmann and Pazzaglia, 2009). Carbonate rocks in the Musone basin are subject to rapid periglacial weathering during glacial periods, resulting in high sediment supply. The carbonate sediment helps plane a strath at the onset of glacial periods, but continuous supply causes the river to aggrade and lose contact with the underlying bedrock strath during the full glacial period. In contrast, thinner alluvial deposits overlying the siliciclastic Bidente basin straths indicate less sediment is produced from glacial weathering and so strath planation occurs throughout the glacial period. In the Le Sueur basin, Minnesota, terrace formation was controlled by glacial retreat and the draining of glacial Lake Agassiz, which lowered base level for the Le Sueur River and created a knickpoint (Gran et al., 2013). Watershed-specific characteristics, unspecified by the authors, caused periodic knickpoint stability along the Waihuka River, a tributary of the Waipaoa River in New Zealand, and created unique sets of strath terraces (Berryman et al., 2010). While all tributaries of the Waipaoa River incised in response to increased discharge and decreased sediment supply in the Holocene (Eden et al., 2001), the Waihuka River terraces differ in age from other tributary terraces because of the lithologic control on knickpoint propagation singular to the Waihuka basin.

The extent to which regional and watershed controls affect strath terrace formation in response to global climate is only discussed for 55 of the 232 strath terraces attributed to climate in our database, thus making it hard to ascertain the extent of regional and watershed controls. Of strath terraces attributed to climate, 68% of these were based on temporal correlation between terrace age and MIS stage, and thus those studies did not consider regional or watershed controls on terrace formation. However, the range in timing of strath formation in response to MIS cycles suggests that regional and watershed controls affect strath formation in many locations. If no intermediary control between MIS climate and strath terrace formation existed, then strath terraces should be planed and incised at similar times. While strath planation predominantly occurs during glacial periods and strath incision is most common in interglacials (Fig. 5), this general trend only holds for 55% and 49% of climatic terraces in our database respectively. Contrasting arid and temperate climates shows that generally more terraces are found in temperate regions, but that no recognizable pattern to when straths are incised and planed relative to regional climate is evident. Because several studies, discussed above, demonstrate that regional climate affects the timing of strath incision and planation, the lack of a systematic trend in Fig. 5 implies that watershed-scale controls add further heterogeneity and complexity to the timing of strath formation in response to climate.

Considering that the effect of global forcings on rivers can be influenced by regional and watershed scale variables, channel response is more varied and complex than shown in Fig. 2. Rather than the single arrow from climate to channel response, the pathway should go through filters of regional and watershed controls. Fig. 7 shows an example diagram of pathways using the subset of studies that we discussed above (Personius, 1995; Formento-Trigilio et al., 2003; Vassallo et al., 2007; Fuller et al., 2009; Wegmann and Pazzaglia, 2009) in regard to the process of strath planation only. Incorporating the spatial levels of controls on strath terrace formation, the pathway from global climate change to channel response branches into distinct routes rather than the single line shown in Figs. 2 and 7A. Each line represents the path through regional and watershed controls on sediment transport capacity and sediment supply that a single location

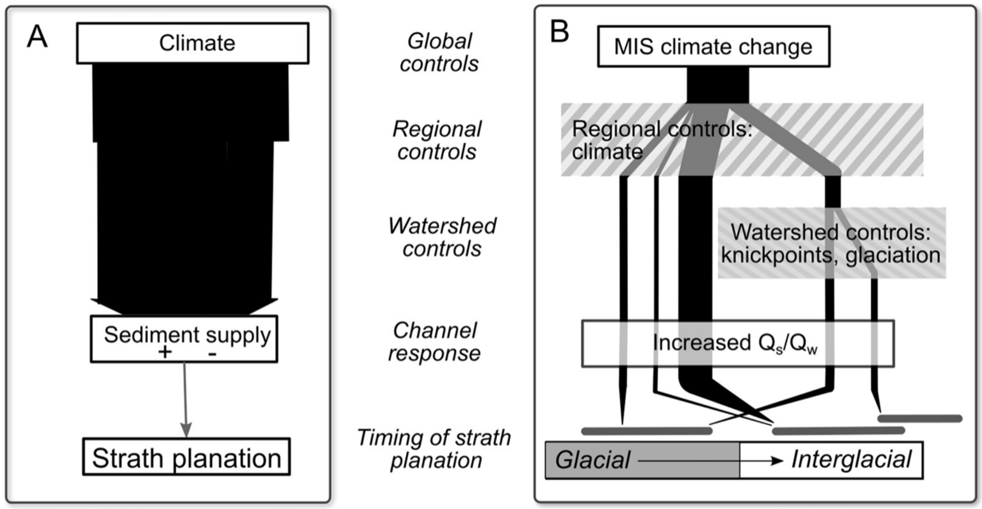

Fig. 7. Pathways from global climate forcings to channel response causing strath planation, contrasting (A) the simplified path from Fig. 2 and (B) the pathways emerging once regional and watershed controls are considered. Black lines in (A) represent the influence of climate on base level, fluvial and glacial erosion, weathering rates, and landsliding rates. In (B), the pathway from MIS climate to planation passes first through regional then watershed controls. The timing of strath planation within the glacial cycle is shown as a gray bar indicating planation in glacial period, interglacials, or transitions between. The thickness of lines represents the number of straths following each path. Each black line represents a different study site and different regional and watershed controls.

experiences. Despite the same original global forcing through which sediment transport and supply are ultimately altered, the timing of strath planation varies depending on the pathway (Fig. 7B).

4.2. Resolving potential forcings for late Holocene strath terraces

Terrace frequency in our database peaks from 4 kya to present (Fig. 6B), yet terrace formation in the late Holocene does not align with the prevalent idea of glacial cycle forcings. Indeed, most terraces formed during this time are unattributed to any forcing. What caused strath terraces to form in the last 4 ky? Without conducting detailed field investigations of the channel conditions at the time of terrace formation, we cannot definitively assign these terraces to a particular forcing. However, below we use literature reviews of Holocene climate and deforestation and databases of volcanic, tectonic, and glacier activity to further assess the likelihood of volcanic, tectonic, glacial, and anthropogenic forcings on late Holocene strath terrace formation.

4.2.1. Volcanic forcings

Comparing volcanic activity in the late Holocene to strath location (Fig. 8) shows that 33 of 52 unascribed late Holocene terraces are located >100 km away from volcanic centers, making it unlikely that

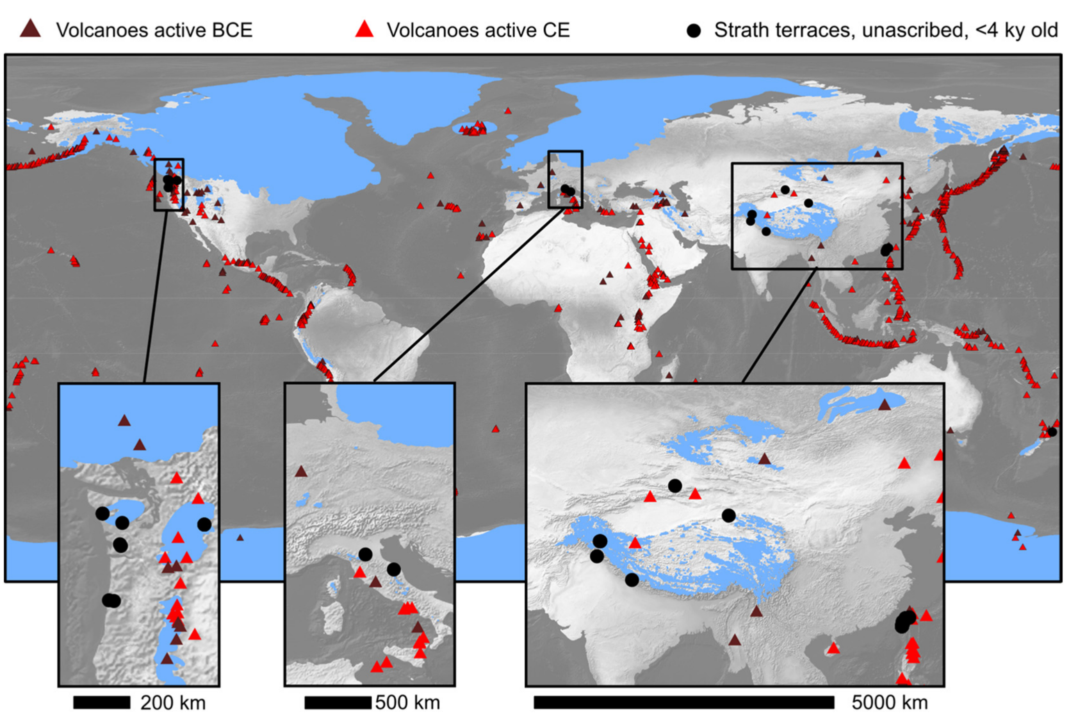

Fig. 8. Locations of late Holocene unascribed strath terraces compared with locations of volcanoes active in the late Holocene and Last Glacial Maximum (LGM) ice extent. Volcanoes are differentiated by whether the last recorded eruption was during current era (CE) or before current era (BCE). The GIS information for the volcanoes and LGM extent are from the Smithsonian Institution (2013) and Ehlers et al. (2011) respectively.

an eruption could trigger strath terrace formation. Of the remaining 19 terraces, 17 are 75 km or farther from active Holocene volcanoes and are also unlikely to be affected by recent eruptions. Lava flows from volcanoes 75 km away are unlikely to dam the river, causing strath planation and incision in the manner documented by Ely et al. (2012). Baynes et al. (2015) found volcanic activity melted ice caps and caused large outburst floods; this is probably not the cause of the late Holocene terraces lacking an identified forcing because none of the 52 terraces are located in regions with active ice cover and with volcanoes (Fig. 8).

4.2.2. Tectonic forcings

Tectonic forcings produced terraces in our compilation through autogenic processes and increased slope caused by long-term changes in uplift rates or fault offset. Autogenic processes create predictable terrace geometries for given lateral and vertical erosion rates because of characteristic meander bend shapes (Limaye and Lamb, 2016). Terrace geometry is not described for all of the unattributed late Holocene terraces, but 31 of the 52 are found in Taiwan, where they were described as short in length and unpaired (Yanites et al., 2010b). Given the vertical erosion rates of 2–3 mm/y on average and up to 11 mm/y (Dadson et al., 2003; Yanites et al., 2010b), lateral erosion rates would need to be ~18–50 mm/y to create short and unpaired autogenic terraces. However, field observations by Yanites et al. (2010a) and Turowski et al. (2008) suggested lateral erosion rates can be in excess of 180 mm/y and locally up to 1000 mm/y. That the morphology and erosion rates of the majority of late Holocene unascribed terraces do not match predicted autogenic terrace form suggests that autogenic forcings are unlikely to be responsible for terrace formation.

Tectonic activity could cause terrace incision in the late Holocene through fault offset or increasing uplift rates. Without detailed site investigation, we cannot adequately determine the late Holocene fault activity at each study location. However, using peak ground acceleration (PGA), we can classify the localities in the manner of Portenga and Bierman (2011), in which sites expected to experience a magnitude 2.0 earthquake or greater in the next 50 years, or a PGA of 2.0, are considered tectonically active. Of the 52 late Holocene unattributed terraces, 49 are in regions with a PGA of 2.0 or greater and are thus classified as tectonically active (Table S1). Of those tectonically active sites, the median PGA is 4.9. The high proportion of late Holocene unattributed terraces in tectonically active regions implies tectonics could have driven the incision of some of these terraces.

4.2.3. Climatic forcings

The age and location of the late Holocene terraces with no identified forcing make it unlikely that they were formed in response to MIS-scale climatic forcings. The influence of MIS cycles, quantified by the number of terraces ascribed to climate, appears to peak at the Pleistocene-Holocene transition and declines toward the present (Fig. 6B). Previous studies in which strath incision occurred in an interglacial period attributed that incision to local base level fall caused by the draining of glacial lakes during ice retreat (e.g., Gran et al., 2013). However, 60% of the late Holocene strath terraces are located in Taiwan, which was sparsely glaciated with mountain glaciers during the LGM (Ono et al., 2005; Fig. 8), thus glaciation likely did not cause ice-dammed lakes or affect local base level. Approximately half of the remaining 40% of late Holocene strath terraces are located in regions that were not glaciated at the LGM at all, further removing the possibility that local base level fall caused by glacial retreat is responsible for strath incision (Fig. 8). Global base level fall during glaciation can cause strath incision; but if this is the case, then the strath planation ages would predate glaciation. However, 43 of the 52 late Holocene terraces are dated using methods that provide a planation age and so are too young to have formed in response to base level fall from glaciation.

Terrace formation at 4 kya does, however, coincide with fluctuations in Asian monsoon strength and temperature for the 31 terraces in Taiwan. Dates for these terraces, all representing terrace planation, cluster at 2.2 kya, which suggests incision occurred after 2.2 kya. Planation of these terraces may be caused by warm and wet conditions in Taiwan that start between 2.5 and 1.5 kya, as quantified by lake pollen records (Liew and Hsieh, 2000). Increased landsliding associated with this wetter period would increase the sediment supply and cause planation. Additionally, monsoon strength increased periodically over centennial to multidecadal scales during the late Holocene (Dykoski et al., 2005). Increased monsoon strength has previously been tied to increased landsliding and sediment supply, which led to strath planation (Hsieh and Knuepfer, 2001) and may be another mechanism by which Holocene climate fluctuations caused the planation of the unascribed terraces in Taiwan. However, the cause of terrace incision after 2.2 kya is unclear; the warm and wet conditions that started 2.5–1.5 kya, and likely contributed to planation, continue to present day.

The remaining 21 terraces in the late Holocene are found in the Pacific Northwest ($n = 10$), the Himalaya ($n = 7$), New Zealand ($n = 2$), and Italy ($n = 2$). Except for three terraces in the Himalaya, terrace age represents planation. Planation may be in response to increased sediment supply during warm and wet conditions, which occurred globally between 1.1 and 0.7 kya, or from glacial advance and increased sediment supply, which occurred from 2.9 to 2.3 kya in the Pacific Northwest and from 0.9 to 0.8 and 0.55 to 0.1 kya in the Himalaya, New Zealand, and Italy (Mayewski et al., 2004; Wanner et al., 2008). The timing of planation in response to glaciation may vary by regional climate (see Section 4.1) but would in general occur in temperate regions during glaciation when sediment is produced, or, for arid regions, after glaciation when wetter conditions promote sediment transport. Comparing planation age against the timing of these glacial advances and warm periods, 12 of the 21 terraces are possibly planed because of climate, while six have planation ages incompatible with interglacial climate variations. The remaining three terraces are inconclusive, based on the age dates and available global climate proxies.

Additionally, interglacial climate fluctuations affect forest composition, which affects the magnitude of sediment retention provided by instream wood. Changing the abundance, size, or durability of wood pieces and wood jams, in turn, can influence how freely sediment can move through the system and thus whether a bedrock channel bed is covered or exposed to erosion (Collins et al., 2016). Wood jam abundance can be altered by variations in fire frequency that are driven by regional climate fluctuations within an interglacial period (Weisberg and Swanson, 2003). The frequency of stand-replacing fires will directly affect the supply of wood for jams, as well as the longevity of existing jams. In Taiwan, wood delivery is often concomitant with monsoon storms (Chen et al., 2013); changing the intensity of monsoons would thus affect instream wood and related sediment retention. Similarly, wood delivery to low-order streams often occurs through debris flows (May and Gresswell, 2003), which would also be sensitive to changes in storminess.

Climate-driven changes to sediment retention could interact with climatic effects on sediment supply and transport (Collins et al., 2016). Weisberg and Swanson (2003) found fire frequency in Oregon and Washington during the last 600 years increased during warmer climatic conditions and decreased during cool conditions. During the warmer periods, stand-replacing fires are potentially more frequent and would periodically decrease wood supply and sediment retention. If so, sediment retention would then be higher during cool periods and lower during warmer periods, potentially resulting in more incision during warm periods and less in cool periods. Since warm conditions tend to be wetter with a higher sediment supply, promoting strath planation, sediment retention changes through stand-replacing fires may lead to punctuated intervals of river incision in a period that is otherwise characterized by planation. The combination of planation from climatically driven changes to sediment supply and incision from fire-caused retention loss could perhaps help explain the formation of some of the unattributed late Holocene strath terraces in our database.

4.2.4. Anthropogenic forcings

Wood supply to river channels and associated changes to sediment retention can also be altered by human activities such as deforestation, logging, and fire suppression. Previous work in Washington State proposed a possible temporal link between splash-dam logging (in which wood jams and associated alluvium were flushed from the system by artificial floods) and the formation of century-old strath terraces (Collins et al., 2016; Schanz and Montgomery, 2016). In Taiwan and the Pacific Northwest, the locations of 41 of the 52 late Holocene unattributed terraces, fire frequency increased with the onset of agricultural activity (Weisberg and Swanson, 2003; Lee et al., 2014) and would have additionally decreased sediment retention over the long term.

To consider if anthropogenically triggered reduction in supply of wood to streams and the associated loss of retention drove the formation of strath terraces in the last 4 ky, we compared terrace age against the earliest record of deforestation and agriculture. Regional deforestation age was found using literature reviews for each strath terrace younger than 8 ky and with no identified forcing (see Table S1 for dates and references). We use the regional deforestation age as a maximum age for when sediment retention could be lowered, as local deforestation and anthropogenic fires (especially in remote upland areas) may have occurred after the onset of regional deforestation.

Strath terrace age is compared against deforestation age in Fig. 9. Only three terraces are dated using techniques that provide the strath incision age; of these, one terrace was incised at the same time as the onset of deforestation and the expected decrease in retention. The other two terraces, incised between 2.5 and 2.7 kya, predate the regional onset of deforestation and thus are not formed in response to anthropogenic retention changes. The remaining 49 terraces are dated using techniques that give a planation age. For those outside of the gray boxes in Fig. 9, planation predates the onset of deforestation. These terraces are possibly influenced by deforestation-related retention changes if terrace incision occurred well after planation. For terrace planation ages within the gray boxes, planation occurred after the regional onset of deforestation. However, retention changes may have occurred after the onset of deforestation; rotation forestry would decrease retention each time harvest occurred, and upland areas were likely logged after the onset of regional deforestation. Additionally, anthropogenic fire regimes could reset retention during any point after the onset of deforestation. Thus, for this latter group of terraces, human-caused decreases to retention remain a plausible influence on terrace formation. In summary, 49 of the 52 unascribed late Holocene terraces could have been influenced by human action and decreased retention.

4.2.5. Late Holocene terrace forcings

The analyses in this section point to several plausible potential drivers of the unascribed late Holocene terraces. While volcanic activity is not a viable forcing for many of the 52 terraces, interglacial climate fluctuations, human-caused loss of wood recruitment and an associated reduction of sediment retention, and tectonic activity are all possible forcings for many of the terraces. Six terraces are possibly influenced by all three, while 46 of the 52 terraces are likely to be influenced by at least two of the aforementioned forcings.

Our examination of late Holocene strath terraces emphasizes the importance of critically assessing the role of global and regional variations in climate, human, and tectonic action on strath terrace formation. Few previous studies have considered the effects of interglacial climate on terrace formation; however, that monsoon strength shifted significantly and glaciers regionally advanced and retreated in the late Holocene suggests that sediment supply and transport may have varied enough to carve and incise strath terraces. Additionally, the influence of variations in fire frequency and forest structure within an interglacial on sediment retention has received little attention but may be important in the formation of Holocene strath terraces. In the last few thousand years, anthropogenic changes to sediment retention are also an important factor in controlling strath incision and have only been explored in a few studies (Collins et al., 2016; Schanz and Montgomery, 2016). Studies of late Holocene terraces should consider watershed and regional climate and anthropogenic factors when determining or ascribing a cause for strath terrace formation.

5. Conclusions

To examine how and when strath terraces form, especially in response to global climate cycles, we compiled a database of 421 dated strath terraces and used terrace age, age dating method, location, and attributed forcing to examine the multiple pathways, modulated by global, regional, and watershed controls, between strath terrace formation and external forcings (climate, tectonics, volcanoes, and humans). The largest portion of strath terraces are attributed to climate in the form of MIS glacial cycles, but the timing of terrace formation is dependent on regional and watershed factors such as vegetation, rock type, glacial proximity, and precipitation patterns. These exert a first-order control on sediment supply and transport capacity and result in terraces attributed to MIS climate forcings being beveled and incised at different times within a glacial cycle. This finding highlights the need to investigate basin-specific landscape response when attributing strath terrace formation to a landscape forcing. The channel variable responsible for incision or planation should be identified, and the pathway between the forcing — climatic, tectonic, volcanic, or anthropogenic — and channel variable investigated in regard to regional and watershed controls. Additionally, dating methods give different constraints on strath age and are often better estimates of strath planation than incision, complicating the correlation of forcings with strath incision.

Strath terraces ascribed to tectonic activity formed in response to steady rock uplift, changing uplift rates, and fault offset. Volcanic forcings included lava dams, which controlled when rivers incised and planed straths, and eruption-induced floods that altered the river slope. Anthropogenic forcings caused planation from post-settlement alluviation but also drove strath incision from gravel mining and loss

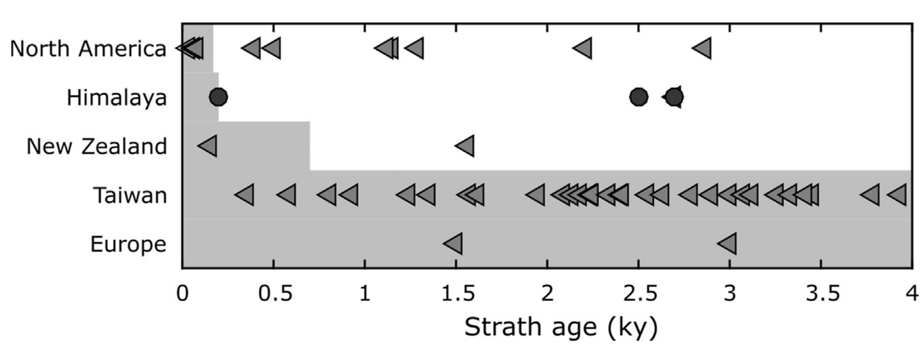

Fig. 9. Ages of late Holocene terraces without an attributed forcing compared with deforestation age for each region. If the terrace age represents terrace planation, the age is marked with a triangle to show that it is a maximum constraint on incision. Terrace ages that date incision are shown as circles. Deforestation age, marked by the gray shading, is for the region in which terraces are found and is a maximum constraint on when local deforestation occurred. All deforestation ages come from literature reviews, as reported in Table S1.

of sediment retention from logging. Sediment retention could also potentially be affected by climate variations that alter fire frequency and forest structure. In the last 4 ky, terrace frequency increased, yet most terraces are unattributed to a forcing. Our results indicate tectonics, interglacial climate changes, and human activity each could potentially have planed and incised strath terraces during this time.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2018.03.028.

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