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Epigenetic gorges in fluvial landscapes

W. B. Ouimet,[1*†] K. X. Whipple,[2] B. T. Crosby,[3] J. P. Johnson[1] and T. F. Schildgen[1]

[1] *Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA*
[2] *School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA*
[3] *Department of Geosciences, Idaho State University, Pocatello, ID, USA*

**Correspondence to: W. B. Ouimet, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.*
E-mail: wouimet@geosc.psu.edu
†Now at Department of Geosciences, Penn State University, University Park, PA 16802, USA.

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Abstract

Epigenetic gorges form when channels that have been laterally displaced during episodes of river blockage or aggradation incise down into bedrock spurs or side-walls of the former valley rather than excavating unconsolidated fills and reinhabiting the buried paleovalley. Valley-filling events that promote epigenetic gorges can be localized, such as a landslide dam or an alluvial/debris flow fan deposit at a tributary junction, or widespread, such as fluvial aggradation in response to climate change or fluctuating base-level. The formation of epigenetic gorges depends upon the competition between the resistance to transport, strength and roughness of valley-filling sediments and a river's ability to sculpt and incise bedrock. The former affects the location and lateral mobility of a channel incising into valley-filling deposits; the latter determines rates of bedrock incision should the path of the incising channel intersect with bedrock that is not the paleovalley bottom. Epigenetic gorge incision, by definition, post-dates the incision that originally cut the valley. Strath terraces and sculpted bedrock walls that form in relation to epigenetic gorges should not be used to directly infer river incision induced by tectonic activity or climate variability. Rather, they are indicative of the variability of short-term bedrock river incision and autogenic dynamics of actively incising fluvial landscapes. The rate of bedrock incision associated with an epigenetic gorge can be very high (>1 cm/yr), typically orders of magnitude higher than both short- and long-term landscape denudation rates. In the context of bedrock river incision and landscape evolution, epigenetic gorges force rivers to incise more bedrock, slowing long-term incision and delaying the adjustment of rivers to regional tectonic and climatic forcing.

Keywords: epigenetic gorge; landslides; river incision; strath terraces; landscape evolution

Introduction

An epigenetic gorge is a bedrock-walled river channel segment that forms as rivers incise into valley-filling deposits and become superimposed on bedrock spurs or entrenched into side-walls of the former valley (Hewitt, 1998) (Figure 1). The term 'epigenetic' refers to the secondary nature of these bedrock gorges, occurring after the formation of the original gorge, and is related to the terms 'epigenetic drainage' or 'epigenetic incision' (see, e.g., von Engeln, 1942). In recent literature, an epigenetic gorge has also been referred to as a 'valley spur cutoff', 'bypass gorge', 'superimposed gorge' or 'modern slot canyon' (James, 2004; Korup *et al.*, 2006; Hewitt, 2006; Pratt-Situala *et al.*, 2007, respectively). In fluvial settings, epigenetic gorges can form in association with landslide dams, alluvial fans or river incision and re-organization following widespread fluvial aggradation. Though not the focus of this paper, epigenetic gorges can also form in association with river blockages and aggradation related to eolian, glacial, volcanic or karst processes.

Epigenetic gorges have been recognized in fluvial landscapes around the world. The majority of epigenetic gorges documented in the literature occur in relation to landslide dams, including examples from NW Himalaya along the Indus River (Hewitt, 1998), central Nepal along trans-Himalayan rivers (Korup *et al.*, 2006; Pratt-Situala *et al.*, 2007), the northeastern Italian Alps along the Vaiont River (Semenza and Ghirotti, 2000) and central Oregon in the lower Deschutes River canyon (Beebee, 2003). One anthropogenic epigenetic gorge that formed in relation to river incision and re-organization following alluvial fan deposition has been documented in the Sierra Nevada Mountains, where fan aggradation during hydraulic mining in the late 1800s diverted Greenhorn Creek, a tributary of Bear River, over a bedrock spur (James, 2004).

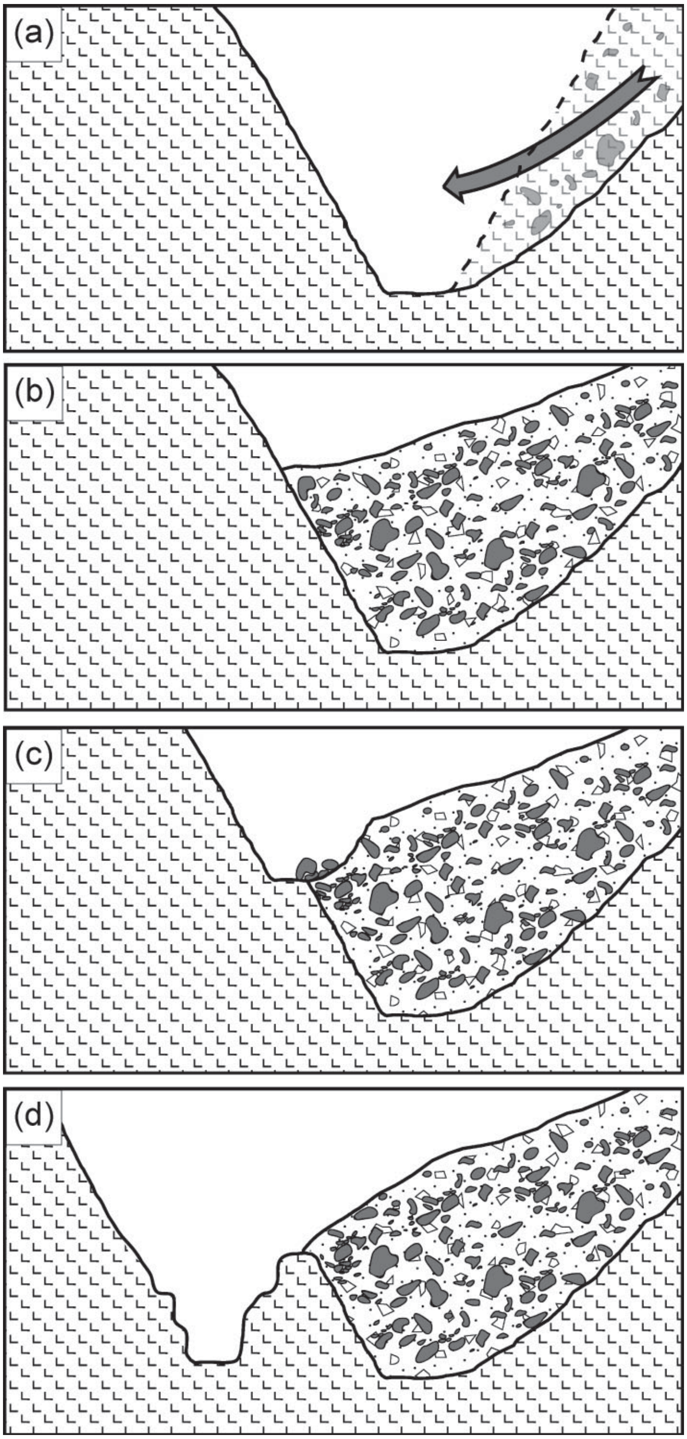

Figure 1. Conceptual model of how large landslide deposits and landslide dams can lead to the formation of epigenetic gorges. The particular example depicted shows an epigenetic gorge forming as a river incises into valley landslide deposits and becomes entrenched into side-walls of the former valley. Sequence: (a) initiation of a large landslide in an incised valley with bedrock valley walls; (b) landslide deposits fill the valley, forming a landslide dam; (c) river starts to cut down through the landslide debris while eroding the bedrock channel walls; (d) river establishes itself into bedrock, abandons the landslide debris and continues to cut an epigenetic gorge.

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Epigenetic gorges in fluvial landscapes

In this paper, we explore the occurrence and significance of epigenetic gorges within actively incising, fluvial landscapes. Our goals are to (1) document the range of fluvial circumstances that can lead to their formation, (2) discuss the dynamics involved in their development and (3) explore implications for studies of river incision and landscape evolution. We begin by introducing conceptual models for the formation of epigenetic gorges in relation to landslides and fluvial aggradation. We support these models and highlight the prevalence of epigenetic gorges in actively incising landscapes by discussing examples from around the world, in rivers that drain the eastern margin of the Tibetan plateau, Peruvian Andes, Colorado Plateau and North Island of New Zealand. Motivated by these examples, we discuss the dynamics involved in epigenetic gorge formation, as well as their significance and implications in the context of studying the rates and processes of bedrock river incision and landscape evolution.

Field Characteristics

Epigenetic gorges are characterized as bedrock walled gorges adjacent to a pre-existing channel and/or valley now filled with landslide or fluvial deposits (Figure 1). Actively forming or recently formed epigenetic gorges typically have narrow valleys, increased channel gradients (possibly containing a waterfall) and wider, low-gradient alluvial river channels both upstream and downstream of the bedrock walled gorge. The age, depth, length and width of an epigenetic gorge determines the coherence of these characteristics. In wide river valleys, epigenetic gorges may simply be new channels cutting down through bedrock that was not the original valley bottom, leading to isolated bedrock ridges in the middle of the valley. Because epigenetic gorges commonly form in relation to landslide deposits and landslide dams, the recognition of epigenetic gorges in the field may be aided by signs of stable landslide dams (i.e. profile knickpoints, and lacustrine and/or fluvial deposition upstream of landslide deposits).

Epigenetic gorges form after the original valley has been cut and are therefore dependent upon the bedrock geometry/configuration of the original valley. Characteristics of valley geometry that influence epigenetic gorge formation include whether the original valley was wide or narrow, whether it was bounded by steep or gentle hillslopes and whether it contained many bedrock spurs and strath terraces close to the active channel, such as might be expected within a river valley with bedrock meanders. None of these attributes will directly generate an epigenetic gorge, but they influence the probability of its formation following a valley-filling event.

Models of Epigenetic Gorge Formation

Landslide Dams

In rapidly incising fluvial landscapes, where high relief and relatively narrow river gorges are common, large landslides often fill river valleys and form landslide dams that inundate upstream channels with water and sediment (Costa and Schuster, 1988). Not all landslide dams fail quickly and/or catastrophically; many stabilize and block river valleys for hundreds to tens of thousands of years, slowly eroding through time (e.g., Ouimet *et al.*, 2007).

Conceptual Model. A conceptual model of how large landslide deposits and landslide dams lead to the formation of epigenetic gorges begins with the initiation of a large landslide adjacent to an incised valley with bedrock valley walls (Figure 1). The landslide deposit fills the valley, forming a landslide dam. Due to the surface topography of the deposit, when water rises to overtop the landslide dam the river is typically pushed against one of bedrock valley walls. The river then starts to cut down through the landslide debris while also eroding the bedrock channel walls. If significant quantities of large bouldery debris are present within the landslide deposit, this material can prevent rapid incision into the landslide deposit, stabilize the landslide dam, and allow the river enough time to sculpt and erode the bedrock channel walls. Once the river is entrenched in bedrock, the river abandons the landslide debris and continues to cut a new bedrock-walled valley. The new valley is an epigenetic gorge.

Landslide Case Study: Eastern margin of the Tibetan Plateau. The eastern margin of the Tibetan Plateau is characterized by deep river gorges cut into regionally uplifted topography (Clark *et al.*, 2006). River gorges in the region, such as those of the Dadu and Yalong Rivers (both major tributaries of the Yangtze River), typically have high local relief, narrow valleys and steep, threshold hillslopes that frequently suffer large landslides (Ouimet *et al.*, 2007). These large landslides inundate river valleys and overwhelm channels with large volumes ($>10^5$ m^3) of coarse material, commonly forming stable landslide dams that trigger extensive and prolonged aggradation upstream. The prevalence of large landslides and stable landslide dams throughout the evolution and rapid incision of rivers on the eastern margin has resulted in many epigenetic gorges.

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The first example within the Dadu River catchment lies near the town of Danba in western Sichuan (SW China). Upstream from Danba, there are significant landslide-related knickpoints on the Dadu mainstem and three of its large tributaries, the Ge Sud Za He, Xiaojin Chuan and Dong Gu He (Ouimet *et al.*, 2007). An excellent example of a landslide-induced epigenetic gorge is located 1 km upstream and SW of Danba along Dong Gu He River (Figure 2). The epigenetic gorge here is cut within a mica-schist and the total amount of epigenetic bedrock incision is 80–100 m.

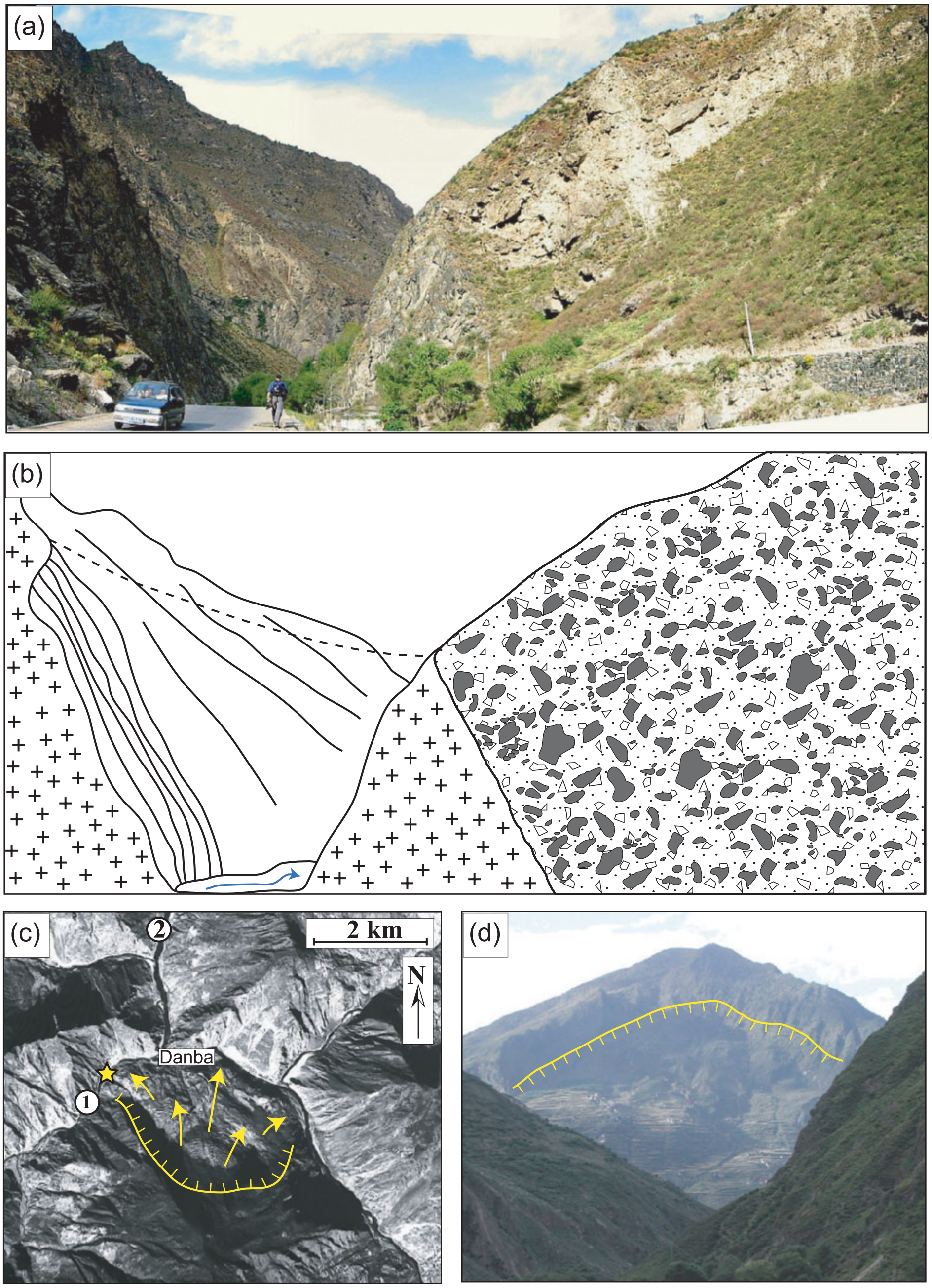

Figure 2. Landslide-induced epigenetic gorge located 1 km upstream of Danba along Dong Gu He River (GPS: 30·8787 North, 101·8735 West). (a), (b) Paired photograph and sketch of the epigenetic gorge viewed from upstream. (c) Corona image of Danba region highlighting the large landslide complex above the city. A star marks the epigenetic gorge location. Locations 1 and 2 indicate where photographs (a) and (d) were taken, respectively. (d) Photograph showing the landslide scarp above Danba. This figure is available in colour online at www.interscience.wiley.com/journal/espl

The active channel through the gorge does not show a significant increase in channel gradient or decrease in channel width through the gorge, though bedrock valley width is much smaller than the valleys upstream and downstream. A second example of a landslide-induced epigenetic gorge lies farther north in the Dadu River catchment, on the Do Qu River ~70 km west of Maerkang (Figure 3). The epigenetic gorge here is cut within Jurassic flysch and the total amount of epigenetic bedrock incision is 100–120 m. The active channel through the gorge is steeper and narrower than alluvial reaches upstream and downstream.

Both of the examples within the Dadu River catchment were of epigenetic gorges that no longer have a significant waterfall or knickpoint associated with them. A smaller scale landslide-induced epigenetic gorge that is actively

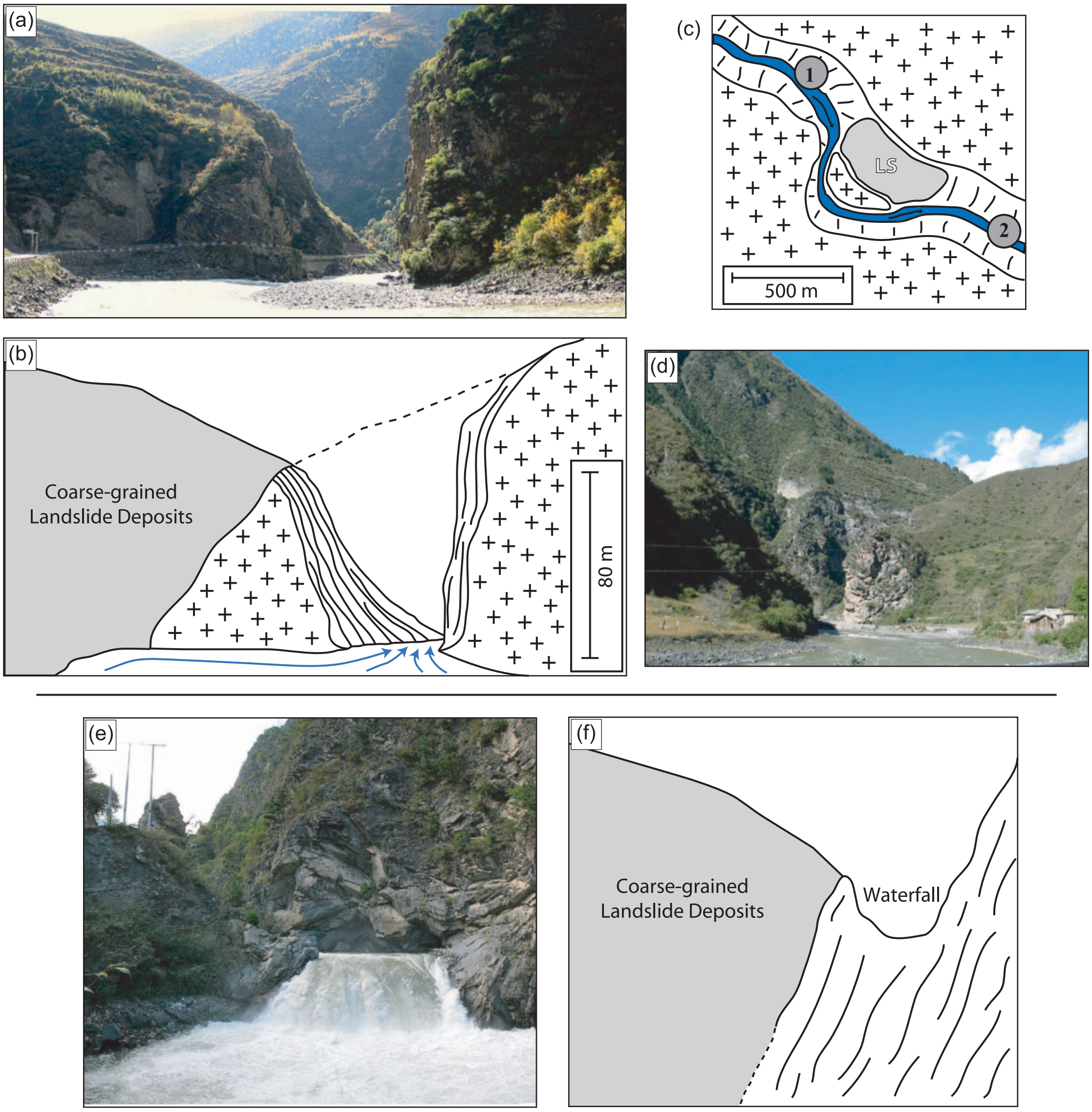

Figure 3. (a)–(d) Landslide-induced epigenetic gorge located ~70 km west of Maerkang on the Do Qu River (GPS: 31·7973 North, 101·5150 West). (a), (b) Paired photograph and sketch of the epigenetic gorge viewed from upstream. (c) Map sketch of the epigenetic gorge. The Dadu River flows from upper left to lower right. Locations 1 and 2 indicate where photographs (a) and (d) were taken, respectively. (d) Photograph of the epigenetic gorge from downstream. (e), (f) Paired photograph and sketch of a landslide-induced epigenetic gorge located on the Somang Qu River (a tributary of the Min River) ~25 km NW of Lixian (GPS: 31·5205 North, 102·9198 West). This particular example has a waterfall, indicating that the epigenetic gorge is actively incising its gorge. This figure is available in colour online at www.interscience.wiley.com/journal/espl

incising its bedrock gorge is found on the Somang Qu River (a tributary within the Min River catchment) ~25 km NW of Lixian. The gorge is cut into Jurassic flysch with total incision into rock of ~30 m, including an active waterfall with 5 m drop (Figure 3). The active channel through the gorge is bedrock and is steeper and narrower than the alluvial reach upstream that contains lake sediments and fluvial sediments that filled a pre-existing landslide dam lake. Directly downstream of the gorge the Somang Qu River contains steep, narrow rapids associated with reworking landslide deposits that contributed to forming the epigenetic gorge.

A final example of a landslide-induced epigenetic gorge on the eastern margin is on the Li Qui River. The Li Qui River is a 190 km long tributary of the Yalong River that runs through Xinduqiao ~50 km west of Kangding in western Sichuan. Landslides have fundamentally altered the morphologic expression of the transient response of the Li Qui to mainstem incision on the Yalong (Ouimet *et al.*, 2007). Within the last 10 km before its confluence with the Yalong, the Li Qui River is extremely steep due to rapid base-level fall and large landslide debris within the present channel. Epigenetic gorges are associated with the landslide deposits in this lowermost section of the Li Qui. Figure 4 depicts a gorge with a total of 50–60 m of bedrock incision cut within granite. The active channel through the gorge is not significantly steeper or narrower through the gorge, though bedrock valley width is much narrower here than either upstream or downstream. We dated the sculpted bedrock strath surface at the top of the epigenetic gorge using cosmogenic radionuclide (^{10}Be) exposure age techniques and found a model age of 3800 ± 300 years before present. Using 48 m as the height above bankfull, this yields a minimum bedrock incision rate associated with the epigenetic gorge of 13 ± 1 mm/yr over this time. This is a time-average minimum incision rate; given that no trace of an initial knickpoint remains, it is likely that the formation and cutting of the epigenetic gorge here proceeded at rates much

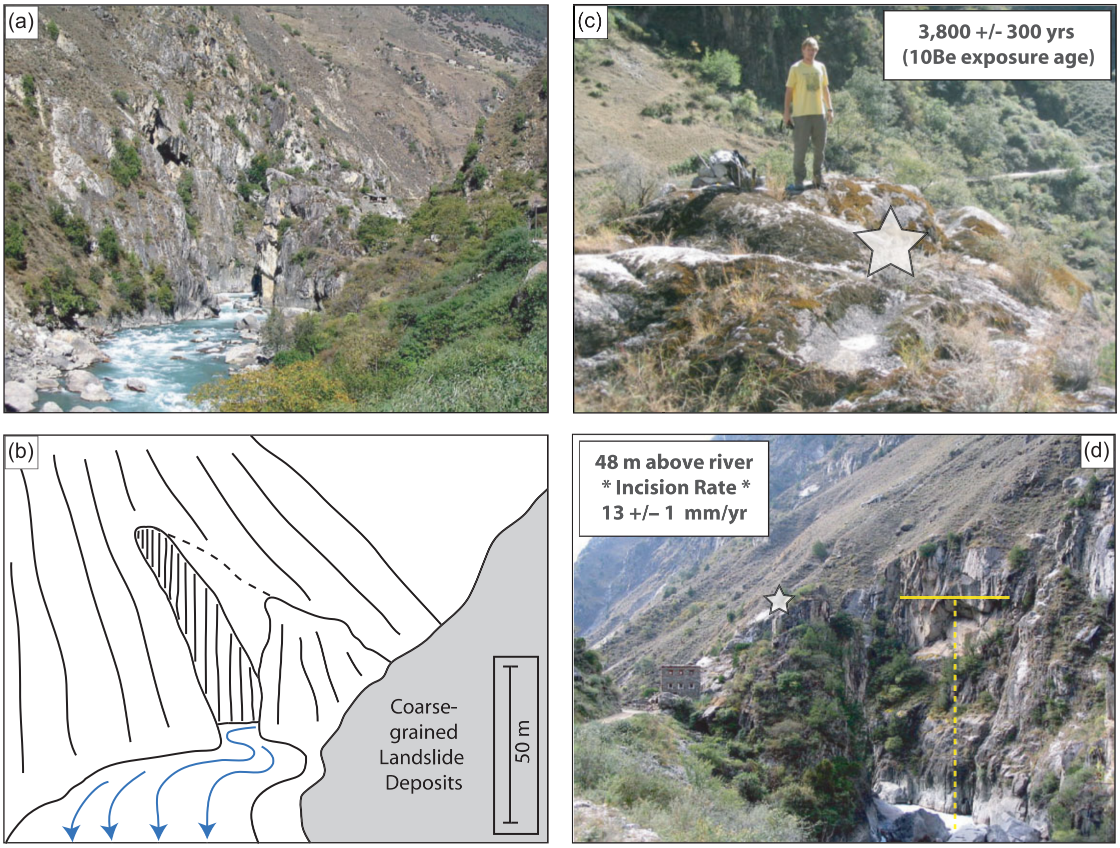

Figure 4. Landslide-induced epigenetic gorge on the Li Qui River, south of Xinduqiao in western Sichuan (GPS: 29·4211 North, 101·1978 West). (a), (b) Paired photograph and sketch of the epigenetic gorge viewed from downstream. (c) Photograph of a sculpted bedrock surface 48 m above the river near the top of the gorge. We dated this surface using cosmogenic radionuclide (^{10}Be) exposure age techniques. The surface age is 3800 ± 300 years old. (d) Photograph of the epigenetic gorge viewed from upstream showing how we calculate a time-average minimum incision rate of 13 ± 1 mm/yr for the gorge. This figure is available in colour online at www.interscience.wiley.com/journal/espl

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greater than 13 mm/yr. This rate is at least one order of magnitude higher than long-term erosion rates in the region (~0·34 mm/yr; Ouimet *et al.*, 2006b), as we will discuss in detail later.

Landslide Case Study: Cotahuasi Canyon, southwest Peru. The Cotahuasi River is located in southwest Peru on the western margin of the Altiplano Plateau in the central Andes. Considered one the deepest river canyons in the world, Cotahuasi Canyon is incised more than 3 km below an uplifted plateau surface (Schildgen *et al.*, 2007). The Cotahuasi valley is characterized by high local relief, narrow valleys and steep, threshold hillslopes. As a result, large landslides and landslide dams are a prominent feature within the canyon and there are many landslide-related epigenetic gorges within the active channel. For most of its length, the Cotahuasi river valley alternates between wide, low-gradient alluvial channels and narrow, high-gradient bedrock-walled sections that contain dramatic rapids. Nearly all the narrow, bedrock walled reaches are landslide and epigenetic gorge related.

The most dramatic example of a landslide-induced epigenetic gorge within Cotahuasi canyon is located near the town of Cotahuasi, at a site called Sipia Falls (Figure 5). In this location, a large volume of landslide material (~0·25 km^3) filled the Cotahuasi valley leading to a landslide dam, the top of which was ~350 m above the pre-landslide river level. Sometime after initial dam breaching and incision, the landslide dam stabilized at ~280 m above the pre-landslide river level. Upstream of Sipia Falls, the landslide-choked valley is mantled with alluvial and lacustrine sediments that attest to the existence of a lake while the landslide dam was stable. This package of sediment sits ~180 m above the modern river level immediately upstream from the falls. Once the upstream lake was filled with alluvium, gravel and sand would have been transported through the falls, acting as tools for abrasion and incision that likely accelerated erosion and incision into the stable landslide dam.

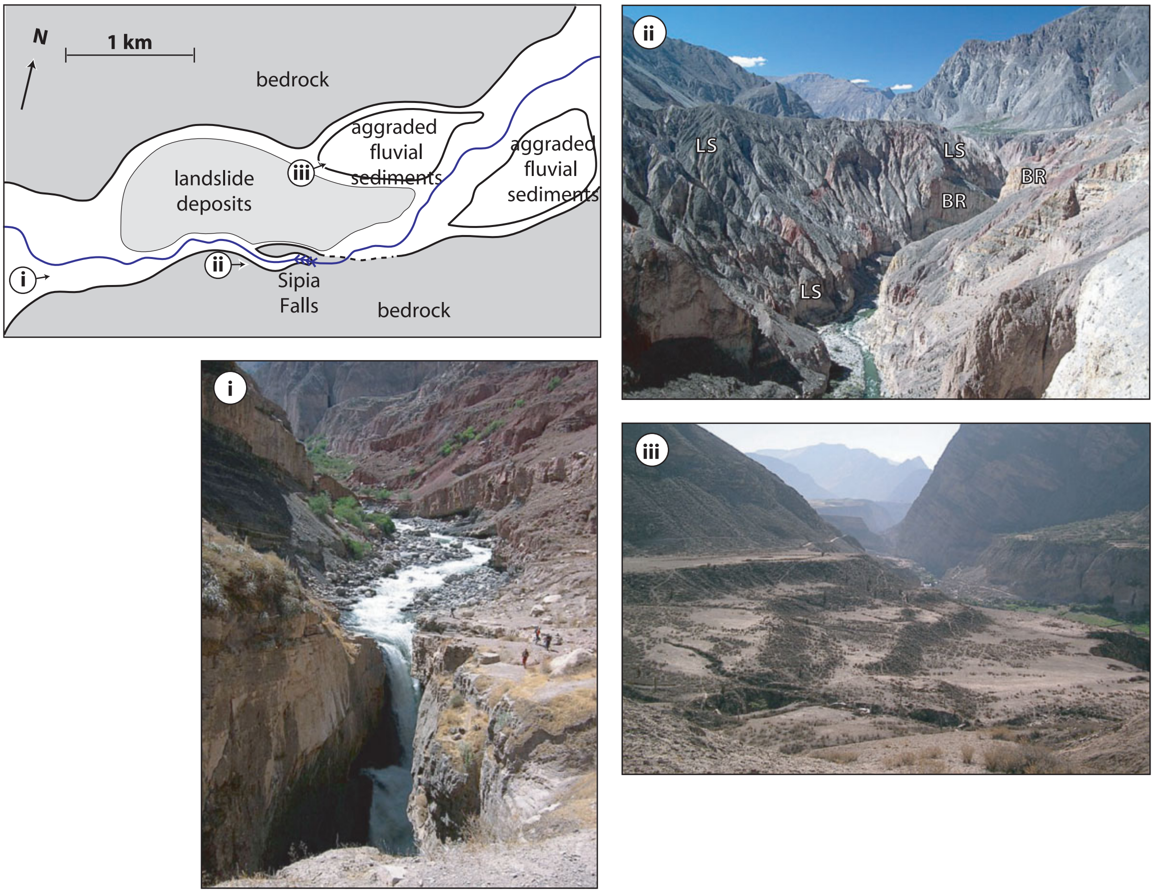

Figure 5. Landslide-induced epigenetic gorge at Sipia Falls within the Cotahuasi River canyon in southwest Peru (GPS: 15·2420 South, 72·9597 West). In the map sketch shown, the Cotahuasi River flows right to left. Locations i, ii and iii indicate where photographs (i), (ii) and (ii) were taken, respectively. In photograph (ii) LS denotes landslide deposits and BR denotes bedrock. This figure is available in colour online at www.interscience.wiley.com/journal/espl

As incision into the dam proceeded, the river eventually came into contact with bedrock along the southern side of the valley, leading to the formation of an epigenetic gorge (Figure 5). Sipia Falls is a waterfall with ~100 m total drop over three steps located within this epigenetic gorge. The top of the falls is held up by massive quartz arenite beds of the Cretaceous Murca and Hualhuani Formations. The bedrock–landslide contact on the northern valley wall is at its highest ~100 m above the top of the falls, constraining the maximum amount of epigenetic bedrock incision at ~200 m. The falls are currently located 490 m upstream from the downstream end of the landslide-filled paleovalley; the upstream end of the landslide fill is another 500 m upstream. The epigenetic gorge at Sipia Falls has already formed, but it has not been completely cut; Sipia Falls represent a bedrock knickpoint actively migrating upstream such that the top of the waterfall is the local base-level for the easily transportable and erodable fluvial sediments that have accumulated upstream.

3.2 Fluvial Aggradation

Conceptual Model. Local or basin-wide fluvial aggradation may occur within a river system for a number of different reasons, such as a climate change or fluctuating base-level. The formation of epigenetic gorges in this context depends primarily on the geometry of the buried paleovalley. Paleovalleys with entrenched bedrock meanders contain spurs and strath surfaces adjacent to the channel. Depending on the magnitude of the aggradation event, these features may be partially or completely buried. Following complete burial, the channel's lateral position is no longer confined to the width of the paleochannel. Instead, the lateral position is controlled by longitudinal variation in sediment supply (e.g. prograding alluvial fans at tributary junctions) or the random switching of channel position on an aggradational bed surface. Following aggradation, the river incises into these unconsolidated fluvial sediments and establishes a path through the valley that often differs from the channel bottom of the buried paleovalley. Therefore, as the river incises, some reaches may incise bedrock spurs and straths of the paleovalley while others will lower easily through unconsolidated fluvial sediment. The longitudinal variation in the magnitude of bedrock incision results in the formation of epigenetic gorges and local knickpoints.

Aggradation Case Study: Trail Canyon, Southeast Utah. Trail Canyon is a tributary of Trachyte Creek, which flows into Lake Powell on the Colorado River above Glen Canyon Dam in southeast Utah. Draining east off Mount Hillers in the Henry Mountains, Trail Canyon is ~17 km long and is incised into sedimentary bedrock units of the Colorado plateau, notably the Navajo Sandstone near its confluence with Trachyte Creek. Base-level control on Trail Canyon and nearby rivers is ultimately associated with dissection of the Colorado plateau throughout the Colorado River catchment. Trail Canyon and other (but not all) channels draining the Henry Mountains contain abundant coarse clasts of resistant diorite that originate from the laccolith intrusions that formed the mountain peaks and are now eroding. Relative to adjacent channels, the coarse sediment load has inhibited overall downcutting due to cover effects of bed armoring (see, e.g., Sklar and Dietrich, 2001). As a result, Trail Canyon has been interpreted to be a transport-limited incising bedrock channel with a smoothly concave longitudinal profile (Johnson *et al.*, 2005a).

The epigenetic gorges in Trail Canyon are the result of river incision and re-organization following regional fluvial aggradation (Figure 6). This aggradation formed extensive fill terraces, 11–15 m thick, presumably associated with late Pleistocene climate change. Along the main-stem of Trachyte Creek approximately 10 km north of its confluence with Trail Canyon, a 7 m high strath covered with 2–3 m of alluvium has been dated to 13 ± 1 ka based on cosmogenic depth profiles (Cook *et al.*, 2006). Where the Trail Canyon valley is wide a fill terrace level 11–15 m above the active bedrock/sediment valley floor is preserved in continuous outcrop; where the valley is narrow the fill terrace remnants are more discontinuous spatially but are consistent in height. A record of less continuous bedrock strath surfaces approximately 0–10 m above the current channel, now typically covered with coarse sediment, indicates that bedrock incision prior to valley filling had reached the current valley bottom but not farther. We have little constraint on whether valley filling and re-incising each occurred approximately monotonically, or whether there was a more complex history of bed aggradation and degradation (reaching a maximum height of fill currently preserved at 11–15 m). In any case, after aggradation stopped, Trail Canyon began incising into the unconsolidated alluvial deposits that had filled the valley, cutting a path through the alluvial sediments that naturally did not everywhere conform to the pre-aggradation river path. When this path was over the strath terraces, Trail Canyon incised through bedrock and formed multiple epigenetic gorges while other sections lowered easily through unconsolidated alluvium (Figure 6). Due to the transport-limited nature of these channels (Johnson *et al.*, 2005a), the epigenetic gorges that formed during this process likely did not produce significant longitudinal profile knickpoints, which contrasts with the landslide related examples described earlier.

The Navajo sandstone is relatively unjointed and sufficiently strong to form dramatic cliffs and overhanging alcoves, but is nonetheless highly erodable in fluvial channels carrying coarse sediment. Recent monitoring studies of bedrock river incision in nearby channels document that incision rates into Navajo Sandstone, though localized along

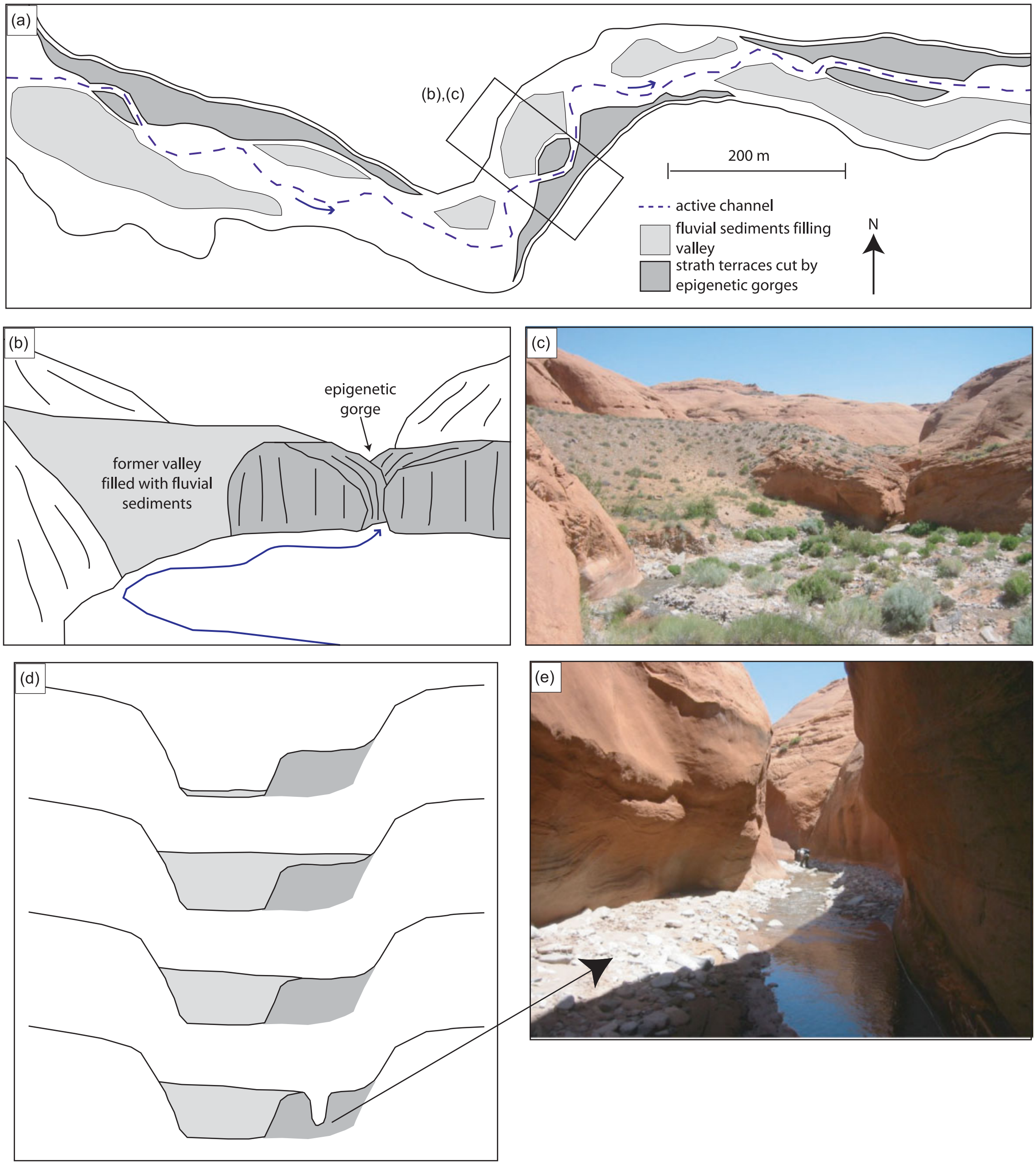

Figure 6. Epigenetic gorges in Trail Canyon, southeast Utah (GPS: 37·8876 North, 110·5398 West). Epigenetic gorges here are the result of river incision and re-organization following fluvial aggradation. (a) Map view of a 1·5 km stretch of Trail Canyon showing where three strath terraces have been cut by epigenetic gorges. Trail Canyon flows from left to right. (b), (c) Paired photograph and sketch of the middle epigenetic gorge viewed from upstream. (d) Schematic model of how fluvial aggradation in Trail Canyon led to the formation of these epigenetic gorges. (e) Photograph of new channel through the gorge. This figure is available in colour online at www.interscience.wiley.com/journal/espl

a steep bedrock channel reach, can exceed 40 cm in a month when snowmelt runoff is high and sustained (Johnson *et al.*, 2005b). Assuming that the ~12–14 ka age measured upstream along Trachyte Creek also correlates with the end of aggradation in Trail Canyon, this suggests that the rate of epigenetic gorge incision is at least 0·6 mm/yr, and the lack of any knickpoints associated with the gorges suggests the incision rate was probably much higher.

Aggradation Case Study: Waihuka River, North Island, New Zealand. The Waihuka River is a trunk stream within the Waipaoa River catchment, located on the northeastern coast of the North Island of New Zealand. A pulse of incision initiated at ~18 ka propagated a wave of incision upstream through much of the Waipaoa River catchment, resulting in the incomplete dissection of an aggraded, low-gradient, relict landscape (Crosby and Whipple, 2006). Prior to incision, fluvial aggradation buried bedrock-floored river valleys between ~30 ka and 18 ka (Litchfield and Berryman, 2005). The bedrock lithology of the Waihuka catchment consists of Miocene clay-rich mudstones and siltstones interbedded with infrequent sandstone and carbonate beds (Mazengarb and Speden, 2000).

The cycle of river incision, aggradation and renewed incision in the Waipaoa basin resulted in the formation of epigenetic gorges, specifically documented along the Waihuka River (Crosby, 2006). The modern longitudinal profile of the Waihuka River (Figure 7) contains a distinct inflection at the exact location where the largest tributary enters the Waihuka. This tributary, the Parihohonu Stream, drains some of the most erosion resistant rocks in the Waihuka catchment, and 18 ka prior to incision produced a well defined alluvial fan that prograded out onto the floor of the Waihuka River valley. During aggradation, the expanding Parihohonu fan forced the Waihuka trunk stream laterally out of its paleochannel and against the opposite side valley wall. During post-aggradation incision, the channel incised into the bedrock along the valley wall rather than re-incising into the alluvium-filled paleochannel preserved under the fan. This same phenomenon was observed at three other location along the 14 km stretch surveyed along the Waihuka River. In the simplified field-surveyed longitudinal profile of the Waihuka River (Figure 7), the positive inflection in the elevation of the strath surface near the Parihohonu fan reflects a greater amount of local bedrock incision

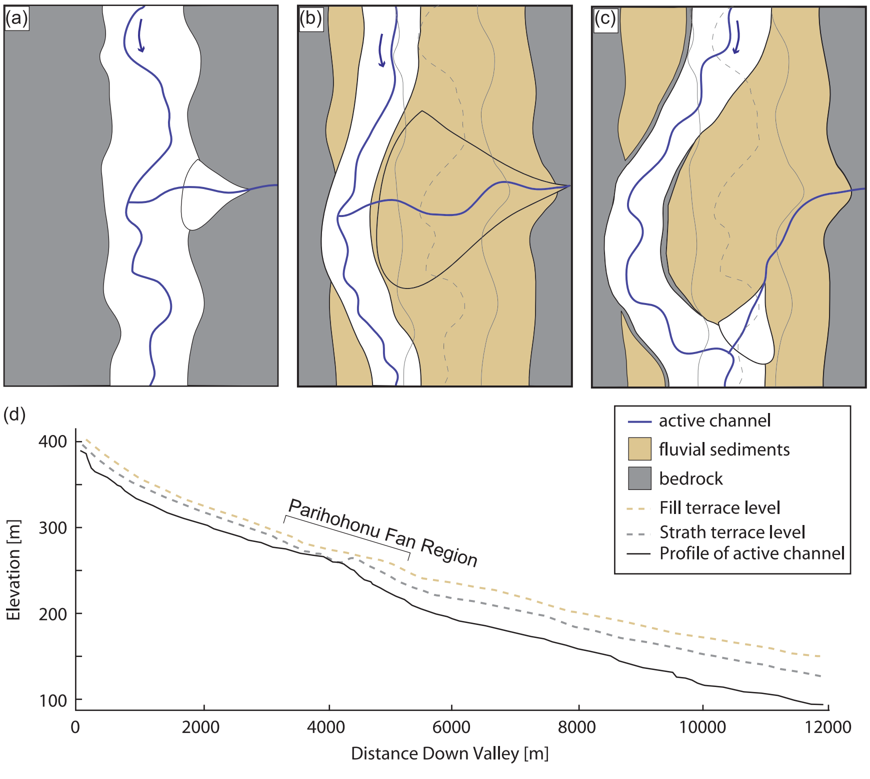

Figure 7. Waihuka River, North Island of New Zealand (GPS: 38·4449 South, 177·6240 East). (a)–(c) Schematic diagrams showing how fluvial aggradation and the influence of a side tributary fan may lead to the formation of an epigenetic gorge. The hypothetical river shown flows from top to bottom. (a) A pre-existing river valley bounded by bedrock with strath terrace levels. (b) Fluvial aggradation fills the valley to level higher than the strath terraces, with additional aggradation focused at a side tributary fan. This side tributary fan pushes the active course of the river to the west. Note the paleovalley and channel (dashed) shaded thinly in gray. (c) Incision into fill stays on the western side of the valley, eventually cutting incision bedrock that bounded the former channel. Note the paleovalley and channel (dashed) shaded thinly in gray. (d) River profile of the Waihuka River with mapped strath and fill levels projected above the profile. The convexity in the middle of the modern profile is the result of displacement between the pre- and post-aggradation Waihuka channels. The Waihuka experienced an epigenetic gorge incision scenario similar to that depicted in the schematic diagram.

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compared to the reaches downstream that reoccupied their paleochannels before incising into their bed. The other locations of epigenetic gorge formation are too small to show on this longitudinal profile.

This example of epigenetic gorge incision has the attributes of both the landslide/alluvial fan model and general fluvial aggradation model. Fluvial aggradation raised the level of the Waihuka River higher than the pre-existing strath level, but the Parihohonu and other alluvial fans were equally important in displacing and guiding subsequent incision away from the former valley center, as well as limiting the lateral mobility of the incising channel.

Dynamics of Formation

The most crucial aspect of the formation of epigenetic gorges is the period of time when rivers begin to rework and incise into valley-filling deposits and come into contact with bedrock that is not the floor of the former valley. After a river has incised into bedrock to a level deeper than its bankfull height, it is likely locked within its new gorge, unless another period of valley-filling occurs and reestablishes the lateral mobility of the channel.

A key issue regarding the formation of epigenetic gorges is why the river cuts a new gorge into bedrock instead of incising into deposits that are presumably easier to erode (i.e. landslide deposits or unconsolidated fluvial sediment). One explanation is that in some cases the nature of valley-filling deposits may actually make it more difficult to transport and incise into them than to erode bedrock. Landslide deposits often include a significant fraction of large (>2 m) erosion-resistant boulders that armor the channel bed as finer material is preferentially transported downstream. This winnowing process condenses the original landslide material into large, interlocked boulders that stabilize the landslide dam and protect the top of the initial deposit from further erosion. These large boulders are not easily moved by large floods and may remain stable for long periods of time, as indicated by advanced fluvial sculpting. They are also significant roughness elements on the bottom of the channel that serve to dissipate stream power associated with typical flood discharges and further reduce the ability of flows to transport material downstream. Similarly, large erosion-resistant boulders may be found within fluvial sediments associated with debris flows and floods. In either situation, the resistant nature of coarse sediments filling the valley may limit the lateral mobility needed to avoid incising into bedrock, allowing enough time for the river to sculpt the bedrock walls or bedrock spurs and incise a new gorge. This does not need to happen as soon as rivers begin to incise the valley-filling deposits. Any time during the reworking of the fill deposits the river can concentrate the coarse debris and reach a threshold where sculpting bedrock and eventually forming an epigenetic gorge is favorable.

A second explanation for why the river cuts a new gorge into bedrock instead of incising into valley-filling sediments is that in relative terms it may never be difficult to incise bedrock. The channel that reworks fill deposits and comes into contact with bedrock may form a steep knickpoint along the river profile (possibly containing a waterfall), with a steep channel gradient and narrow channel width generating increased stream power necessary to erode the bedrock rapidly (Finnegan *et al.*, 2005). Furthermore, there may also be abundant sediment transported over the bedrock to act as tools to aid abrasion and help erode the bedrock (see, e.g., Sklar and Dietrich, 2001). Again, this does not need to happen as soon as rivers begin to incise the valley-filling deposits. Any time during the reworking of the fill deposits the river channel can become steep enough or have enough tools for erosion to favor sculpting bedrock and the formation of an epigenetic gorge.

The process of sculpting and incising into bedrock during the formation of epigenetic gorges may form strath terraces. In general, the erosion taking place on valley side-walls in the early stages of an epigenetic gorge (perhaps steered by landslide deposition or tributary debris flow fans) illustrates one way in which valley-filling events can lead to the formation of strath terraces, regardless of whether or not an epigenetic gorge results. Strath terraces can also form within the gorge itself during incision, or during reworking and incision of fluvial sediments that are upstream of the gorge or associated with widespread aggradation. The propensity for these situations to form strath surfaces will be greater in rivers flowing over weak, soft rock than in those flowing over hard, erosion resistant rocks (Montgomery, 2004).

All factors that affect bedrock river incision are potentially involved with epigenetic gorge formation since the fundamental aspect of their formation is incising bedrock. Rock strength (lithology type, jointing, fractures, degree of weathering etc.), tools for abrasion, sediment cover and stream power are all elements to consider (Whipple and Tucker, 1999; Hancock *et al.*, 1998; Sklar and Dietrich, 2001). In terms of the role of rock strength, certain rock types may be weak enough that sculpting and incising bedrock is relatively easy, or so resistant to erosion that the only way to initiate epigenetic gorge formation is to concentrate coarse deposits, limiting lateral mobility and forming the steep, narrow channel necessary to erode harder rock. It follows that landslide-related epigenetic gorges may emphasize the importance of coarse valley-filling sediments in formation, potentially allowing gorges to incise regardless of rock strength; where as the likelihood of epigenetic gorge formation following fluvial aggradation may be more a function of the strength of the bedrock to be incised, as well as valley geometry. In the case of alluvial fans (in particular debris flow fans), it may be the continuous deposition of coarse sediments that influences the probability of their formation, rather than a single valley-filling event. In these situations, the persistent, localized delivery of coarse sediment to one side of the trunk stream may continually drive the river laterally toward the opposite side of the river valley, focusing erosion against the side-walls of the former valley.

The case of epigenetic gorges forming in relation to river incision and re-organization following fluvial aggradation is strongly dependent on the new course of the river as it incises into fluvial sediments and the bedrock geometry of the former valley (much more so than landslide examples). At some point when the river is entrenched within the fluvial deposits it reaches bedrock, which may or may not be the original bedrock valley floor. At this point the river can keep incising into bedrock, or laterally erode the banks. In contrast with the landslide and debris flow fan related examples, these fluvial aggradation examples typically do not have significant amounts of coarse material to limit lateral mobility and facilitate epigenetic gorge formation. The fact that epigenetic gorges form at all under these conditions suggests that that sculpting and incising bedrock must be easy, or at least that a river's ability to incise is not limited by the strength of the rock. This second point suggests that rivers in which these kinds of epigenetic gorge form are probably often essentially transport limited, meaning that incision into bedrock is regulated by a river's ability to transport sediment, as opposed to detachment limited, where incision into bedrock is regulated by a river's ability to detach and abrade the bedrock channel bed (Howard, 1994; Whipple and Tucker, 2002). Only in transport-limited rivers would you expect channel incision to proceed in the same manner regardless of whether the channel bottom consists of bedrock or sediments, leading to smooth transitions between reaches of channel incising bedrock (epigenetic gorges) and fluvial sediments. This interpretation likely applies to both the field examples presented earlier in Utah's Henry Mountains and New Zealand's Waihuka river basin.

Bedrock River Incision and Landscape Evolution

The prevalence of epigenetic gorges in actively incising landscapes has important implications for the rates and processes of bedrock river incision and for landscape evolution in general. In this section, we discuss the significance of epigenetic gorges in terms of bedrock strath terrace studies, short-term bedrock incision rates, the overall influence of large landslides on river incision and the long-term effect of epigenetic gorges on landscape evolution.

Bedrock strath terrace studies

River channels are the skeletal network of a landscape through which signals of base-level fall and hydrological changes induced by tectonic activity or climate variability are transmitted (Whipple, 2004). As recorders of bedrock river incision, therefore, fluvially sculpted bedrock surfaces and strath terraces adjacent to the active channel or up on bedrock valley walls are commonly used to study the rates and patterns of landscape adjustment to such forcing (see, e.g., Merritts *et al.*, 1994; Pazzaglia *et al.*, 1998; Burbank and Anderson, 2001; Hancock and Anderson, 2002). The age and height of abandoned strath terraces can provide necessary constraints for determining incision history and incision rates (see, e.g., Burbank *et al.*, 1996; Leland *et al.*, 1998; Hsieh and Knuepfer, 2002; Wegmann and Pazzaglia, 2002), and mapping the longitudinal pattern of strath terraces can be used to reconstruct paleoriver profiles. The validity of these interpretations, however, depends upon key assumptions regarding the formation and abandonment of strath terraces and fluvially sculpted surfaces. These assumptions are that (1) the surface dated has not been eroded, buried or otherwise modified in any significant way since abandonment, (2) the surface dated was formed during the original incision of the valley such that the age of abandonment and the height of the strath above the modern river bed record the average rate of incision into bedrock over that time interval and (3) this local bedrock incision is directly related to overall lowering of the river bed. The greatest uncertainty in interpretation arises where only small, isolated patches of strath terraces are preserved, as is common in areas of rapid rock uplift and incision (see, e.g., Burbank *et al.*, 1996; Pratt *et al.*, 2002). However, even where regionally extensive strath terraces can be mapped and correlated with confidence (see Merritts *et al.*, 1994), the age of ultimate abandonment of the strath surfaces does not necessarily correspond to a stage in the original incision of the valley; cut-and-fill cycles can complicate the record of strath heights and ages. Epigenetic gorges are a key landform element that records evidence of such complications and therefore attention should be given to searching for them.

Epigenetic gorge incision, by definition, post-dates the original incision that cut the subsequently filled valley. Strath terraces and sculpted bedrock walls that form in relation to epigenetic gorges should not be used to infer long-term incision rates or to study landscape adjustment induced by tectonic activity or climate variability. As a result, caution is advised when interpreting rates and patterns of bedrock incision derived from strath terraces in fluvial landscapes that experience a high frequency of large landslides or those have had large cut-fill cycles related to fluvial aggradation, such as has been documented in the Himalaya and along the eastern margin of the Tibetan plateau (Burbank *et al.*, 1996; Ouimet *et al.*, 2007). In general, this caution applies to all strath terraces that may be thin lateral remnants of thicker fill terraces in which the river re-incised in the same location. Epigenetic gorges, where present, serve to positively identify the existence of incision and aggradation cycles, which are superimposed on background bedrock incision rates. Estimating long-term incision rates from strath terraces in these situations depends upon the scale and frequency of the cycles in reference to the dated strath. Strath terraces will give the long-term average rate of channel lowering only in the case where they integrate periods of both incision and aggradation. This suggests that higher strath terraces may be better for determining long-term incision rates, while low strath terraces may speak more to bedrock river abrasion and how fast rivers are able to cut bedrock while incising. This will be discussed below.

Another caution for bedrock strath terrace studies related to epigenetic gorge incision is that localized rapid incision of epigenetic gorges will often be associated with short-lived, very steep knickpoints or knickzones. Thus, analyses of the relation between bedrock incision rate and channel gradient or stream power must recognize that the channel gradient may well have been much greater (and possibly channel width less) during the times of rapid incision (Stock and Montgomery, 1999; Finnegan *et al.*, 2005). Conversely, if paleochannel profiles are sufficiently well preserved, or if a river is caught in the act of carving an epigenetic gorge (such as the Sipia Falls example in Peru or the upper Ukak river in Alaska – Whipple *et al.*, 2000), they can be exploited as excellent natural experiments in river incision into bedrock. The Ukak example is an epigenetic gorge that formed during re-incision of Upper Ukak River valley following a 1912 ash flow deposit that buried the prior valley. The rate of bedrock incision now associated with the epigenetic gorge within the Ukak River is ~10 cm/yr (Whipple *et al.*, 2000), greatly exceeding any plausible long-term bedrock incision rate in this landscape.

Short-term bedrock incision rates

Short-term bedrock river incision rates calculated from strath terraces related to epigenetic gorges are likely to be higher than long-term trunk river exhumation/incision rates. The Li Qui example discussed earlier is an excellent illustration of this situation. The sculpted bedrock surface we dated is a strath surface that was presumably cut during the initial phase of epigenetic gorge formation. Within 3 km of this epigenetic gorge, long-term rates of landscape exhumation and short-term rates of basin-wide erosion are well constrained. An estimate of the apparent long-term erosion rate is ~0·34 ± 0·04 mm/yr, derived from an age–elevation transect of (U–Th)/He ages in apatites and zircons (Ouimet *et al.*, 2006b). This long-term erosion rate applies to the period of time between 14 and 1·2 Ma. It rate may have increased in the last 1·2 Ma in response to local uplift and exhumation, but only to a rate as high 1 mm/yr (Ouimet *et al.*, 2006b). The short-term erosion rate, which is derived from measurements of ^{10}Be in quartz river sand from two river basins (35 and 94 km^2), averages to ~0·33 mm/yr for the last 2500 years (Ouimet *et al.*, 2006a). The short-term bedrock river incision rate associated with incision in the Li Qui River epigenetic gorge, as mentioned earlier, is more than 13 mm/yr, almost two orders of magnitude higher than these short- and long-term rates. Similarly, anomalously high rates of bedrock river incision related to epigenetic gorges have been documented in Nepal, more than 13 mm/yr (Pratt-Sitaula *et al.*, 2007), and in the Sierra Nevada, more than 25 cm/yr (James, 2004), both of which are significantly higher than long-term, background rates.

Strath terraces can form during reworking of fluvial sediments upstream of an epigenetic gorge or landslide dam site, or anywhere within a stretch of river experiencing widespread fluvial aggradation. High laterally mobility of a river relative to its incision allows it to move easily across the valley, potentially cutting strath terraces along bedrock channel banks and/or sculpting bedrock walls. A suite of strath terraces on the Dadu River 45 km north of Luding illustrates the implications of such a scenario (Figure 8). At this site we sampled two sculpted bedrock surfaces adjacent to the channel to obtain a cosmogenic radionuclide (^{10}Be) exposure age of the quartz in the bedrock. One of surfaces studied was 45 m above the present channel, the other 17 m. Both surfaces were dated at ~50 ka, within error of each other; this age yields minimum incision rates of ~0·9 mm/yr and ~0·3 mm/yr, respectively. We interpret these strath surfaces as recording a period of time when the Dadu River aggraded to a level at least 50 m above modern river elevation. Then, as incision into the fill proceeded, these surfaces were sculpted and the cosmogenic clock reset. The same age for both strath levels indicates that these surfaces were generated at the same time, consistent with either rapid aggradation or rapid re-incision into fill at the site. We acknowledge that other plausible, if less likely, explanations exist, such as an abrupt stripping event that removes an alluvial or colluvial cover that had previously shielded the site.

A large river, in this case the Dadu, could easily have rapidly incised unconsolidated fluvial sediments and would have had abundant tools for sculpting bedrock surfaces quickly. In a similar example, rapid fluvial aggradation and subsequent incision that reset the ages of sculpted bedrock adjacent to a large channel has been documented on the Marsyandi River, in central Nepal (Pratt *et al.*, 2002). In our example, we found no evidence of fluvial sediment on strath terraces, and no evidence of landslide dams, epigenetic gorges or widespread fluvial aggradation within 10 km upstream or

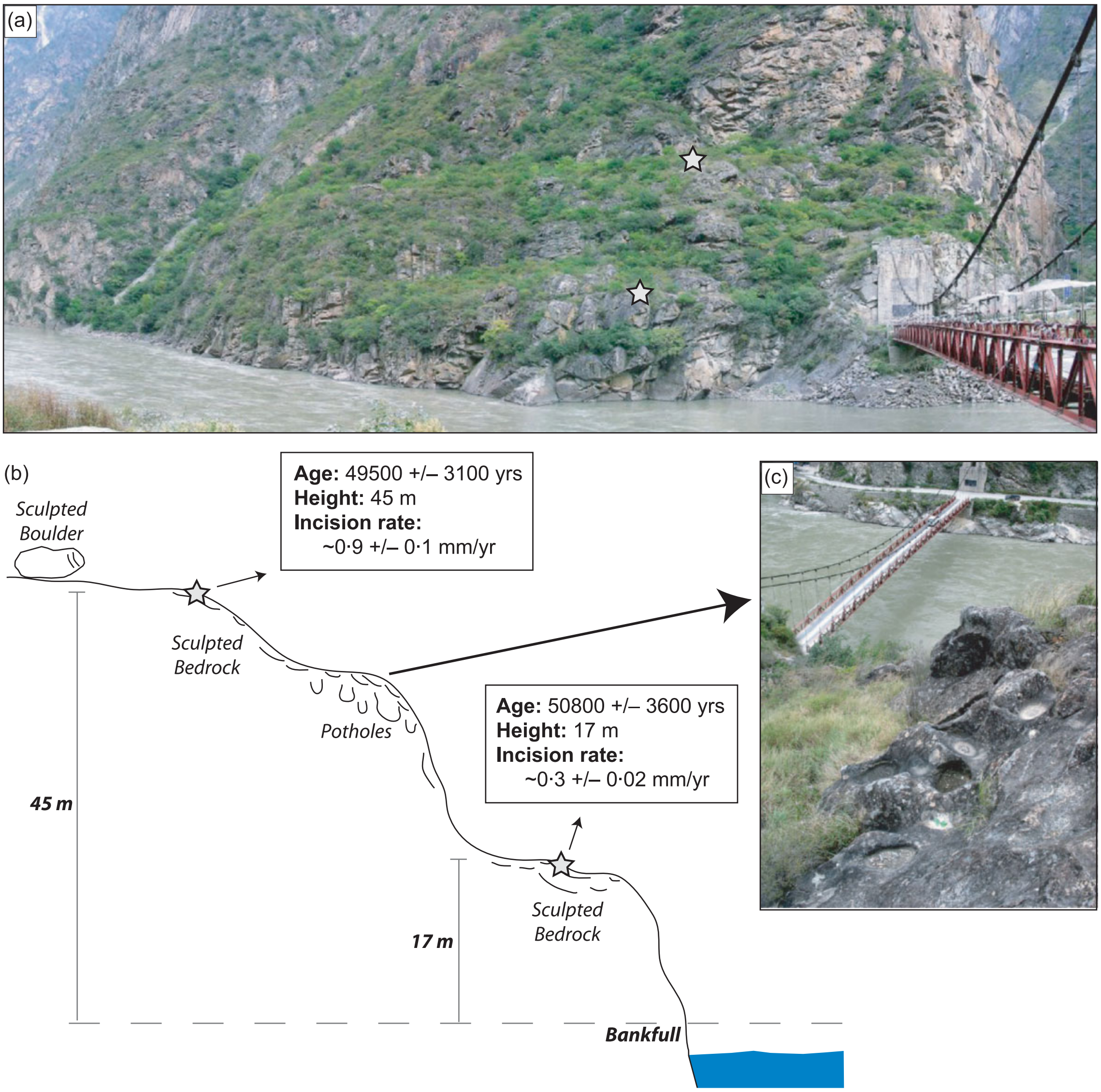

Figure 8. Bedrock straths along the Dadu River, ~45 km north of Luding (GPS: 30·2966 North, 102·1729 West). We dated two sculpted surfaces adjacent to the channel at this site, one 45 m above the present channel, the other 17 m. Both surfaces were dated at ~50 ka, within error of each other, yielding minimum incision rates of ~0·9 and ~0·3 mm/yr, respectively. These strath surfaces record rapid incision into fluvial sediment that had filled the Dadu River to a level at least 50 m above modern river elevation. This figure is available in colour online at www.interscience.wiley.com/journal/espl

downstream of this site. This emphasizes two points: (1) in large, actively eroding and incising river gorges, sediments related to the valley-filling event are easy to remove, and (2) the effects of landslides and epigenetic gorges may be felt far upstream and downstream of the location of the valley-filling event. If we had only dated one of the two strath terrace surfaces on the Dadu, we would not have been able to tell that their formation was related to fluvial aggradation, and would have mis-interpreted the bedrock river incision rate calculated from the strath surface exposure age.

Landslides, epigenetic gorges and landscape evolution

Bedrock river incision can be intermittent on millennial timescales due to the effects of landslide dams. Stable, gradually eroding landslide dams create mixed bedrock–alluvial channels with spatial and temporal variations in

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incision, ultimately slowing long-term rates of river incision and reducing the total amount of incision occurring over a given length of river (Ouimet *et al.*, 2007). Landslides influence river channels and lead to reduced river incision efficiency by setting the percentage of channel length buried by landslide related debris. As a result, the longer it takes a river channel to incise into a landslide dam and remove all landslide-related deposits, the more influence landslides and landslide dams have on river incision. The fact that landslide deposits may deflect rivers over bedrock ridges and lead to epigenetic gorges enhances dam stability and adds to this influence.

Within models of bedrock river incision and landscape evolution, the influence of epigenetic gorges strengthens the overall influence of landslides, but, much more broadly, epigenetic gorges increase the potential for any valley-filling event to influence landscape evolution. Epigenetic gorges force rivers to incise more bedrock, slowing long-term incision. In addition, they act as bedrock spillways that regulate the base-level for upstream channels and the adjustment of rivers to regional tectonic and climatic forcing. During their formation, all epigenetic gorges are stable dams that have an associated wedge of sediment built behind them. This wedge of sediment exists until the epigenetic gorge incises to a level lower than the bedrock valley floor of the former valley. Along any given stretch of river where epigenetic gorges occur, therefore, river incision efficiency is reduced for the period of time associated with cutting the gorge.

The end result of all these effects on river channels is that epigenetic gorges cause variable incision rates in space and time within river drainages, even if the landscape is in a long-term steady state balance between rock uplift and erosion. Epigenetic gorges also have important effects on valley geometry. They can directly drive lateral migration of channels (which is missing from most landscape evolution models), cause new landslides by undermining valley sides, drive valley widening and ultimately lead to lateral migration of drainage divides.

Finally, epigenetic gorges (in particular those that are landslide related) broadly speak to a dynamic coupling between river incision and hillslope processes in landscape evolution. As rivers incise, they must erode bedrock and transport all the sediment supplied to them from the entire upstream drainage basin, tributaries and adjacent hillslopes. When this debris is coarse (e.g. deriving from small rockfalls to the large landslides discussed here and by Ouimet *et al.*, 2007) or when it leads to the formation of epigenetic gorges, river incision is influenced. The overall rate of stream incision and, over long time spans, the channel gradient may be conditioned by the necessity to transport and erode the coarse debris (e.g., Howard, 1998) or to incise bedrock within an epigenetic gorges.

Conclusions

Epigenetic gorges are a prevalent feature in rivers with valley-filling and re-incision sequences. Valley-filling events that promote epigenetic gorges can be related to landslides (landslide deposits and stable landslide dams), debris flows, alluvial fans or widespread fluvial aggradation. Re-incision results from shutting off the increased sediment flux or simply re-working a localized deposit. Epigenetic gorges form when landslides or alluvial fans push rivers against opposite valley walls and become entrenched into bedrock, or more generally after a period of fluvial aggradation when a river incises into the fill and is superimposed on a bedrock spur of the former bedrock valley.

Epigenetic gorges highlight the intermittent and episodic nature of bedrock incision in actively incising rivers both spatially and temporally. They are related to autogenic processes within actively incising rivers, indicating that isolated bedrock gorges and mixed bedrock–alluvial channels are part of the regular process of long-term incision. Incision can be rapid, then dormant, rapid then dormant. Epigenetic gorges also have important implications in the context of bedrock river incision and landscape evolution. They are a process by which valleys widen their bedrock valleys; they slow the overall long-term river incision and transient adjustment as rivers often have to re-incise a certain percentage of their bedrock gorges, enhancing the landslide influence in general. The rapid incision occurs in part because of the high number of tools for incision (fluvial sediments) that build up behind the dam and the high stream power associated with river channels these bedrock gorges.

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