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Bedrock fracture influences on geomorphic process and form across process domains and scales

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ABSTRACT: Fractures are discontinuities in rock that can be exploited by erosion. Fractures regulate cohesion, profoundly affecting the rate, style, and location of Earth surface processes. By modulating the spatial distribution of erodibility, fractures can focus erosion and set the shape of features from scales of fluvial bedforms to entire landscapes. Although early investigation focused on fractures as features that influence the orientation and location of landforms, recent work has started to discern the mechanisms by which fractures influence the erodibility of bedrock. As numerical modeling and field measurement techniques improve, it is rapidly becoming feasible to determine how fractures influence geomorphic processes, as opposed to when or where. However, progress is hampered by a lack of research coordination across scales and process domains. We review studies from hillslope, glacial, fluvial, and coastal domains from the scale of reaches and outcrops to entire landscapes. We then synthesize this work to highlight similarities across domains and scales and suggest knowledge gaps, opportunities, and methodological challenges that need to be solved. By integrating knowledge across domains and scales, we present a more holistic conceptualization of fracture influences on geomorphic processes. This conceptualization enables a more unified framework for future investigation into fracture influences on Earth surface dynamics. © 2018 John Wiley & Sons, Ltd.

KEYWORDS: fracture; erosion; process; geomorphology; topography

Introduction

Earth's surface can be characterized on a broad scale by discontinuities, or fractures, which separate otherwise continuous Earth materials. As a first-order approximation, fractures have been hypothesized to be the dominant control on erosion rates, effectively acting as the mechanism by which tectonic stress shapes the landscape (Molnar *et al.,* 2007). Fractures set the primary boundary condition for plucking by glaciers and rivers, which may be the most efficient mechanism of eroding bedrock (Hallet, 1996; Whipple *et al.,* 2000a), and in doing so can set the speed limit for the evolution of landscapes (Whipple, 2004). Investigators have long recognized the importance of fractures in influencing hillslope stability (Gilbert, 1904); the location and orientation of channels from the scale of gullies to entire river networks (Hobbs, 1905; Gilbert, 1909); and erosion rates (Bryan, 1914). However, we lack a unified theory of how fractures impact the development of Earth's surface across spatial and temporal scales and across diverse geomorphic process domains (Montgomery, 1999).

In recent years, the focus of geomorphology has shifted towards understanding geomorphic processes utilizing conceptual models to inform geomorphic laws that describe the transport of Earth material across scales and domains (Dietrich *et al.,* 2003; Wohl *et al.,* 2016). For processes influenced by fractures, this effort has led to important conceptualizations and models of surface processes such as fluvial plucking (Chatanantavet and Parker, 2009; Lamb *et al.,* 2015), glacial quarrying (Hallet, 1996), coastal erosion (Naylor and Stephenson, 2010), and hillslope stability (Clarke and Burbank, 2010; Loye *et al.,* 2012). In these domains, we can rudimentarily model fractures acting as controls on the rate, style, and spatial occurrence of geomorphic processes. However, the lack of synthetic understanding of the impacts of fractures on geomorphic process and form is starting to limit our progress. For instance, research into the quarrying of fracture-bound blocks by glaciers has progressed to include fracture orientation as an explicit control on quarrying (Lane *et al.,* 2015), whereas research into fluvial plucking is only just starting to suggest a potential role of orientation in controlling erosion rate (Lamb *et al.,* 2015). Synthesis of the various impacts of fractures on geomorphology will facilitate the application of knowledge across process domains to both fundamental and applied research questions.

Here, we review current understanding of the mechanisms by which fractures influence the rate, style, and location of erosion, as well as feedbacks between erosion and fracture propagation (the widening or lengthening of a fracture). We organize our review into three sections: (1) effects of fractures on erosion rates and styles, (2) fracture controls on the shape, orientation, and location of landforms and erosion, and (3) feedbacks between erosion and fracture propagation that act to either accelerate or retard further erosion. We then synthesize this understanding across process domains and scales and identify logical next steps to address existing knowledge gaps.

Definition of scope

We use the definitions of Selby (1993) to clarify the meaning of fracture as any parting that allows open space or discontinuity between otherwise intact masses of Earth material. Specific types of fractures such as joints (fractures with no shear along the fracture surface), faults (fractures with displacement), and fractures following foliation or bedding will generally not be differentiated in terms of their impacts on geomorphic processes (namely erosion and weathering), which tend to exploit fractures as weak zones, regardless of their formation mechanism. Faults will not be treated as distinct from joints other than in the sense that they commonly correspond to areas of high fracture density (number of fractures per unit area or length) and potentially lithologic discontinuity.

We focus on the effects of fractures on geomorphic process and form, although we provide a brief overview of fracture generation. We refer readers to rock mechanics literature for a more detailed examination of fracture generation (Gudmundsson, 2011; Eppes and Keanini, 2017). Fractures are formed by the response of rock to stress. The processes by which fractures form can be roughly divided into those that affect broad regions, due to either widespread temperature change or broadly exerted pressures, and those that are more local, creating more variable fracture geometry in a smaller area. Regional fracture-forming processes tend to form more predictable, spatially uniform, or gradually varying fracture geometry. Local processes tend to form spatially constrained, highly variable fracture geometries. Both sets of processes occur in most rock masses. Complex fracture patterns can occur from multiple discrete episodes of stress applied to a material in different directions and magnitudes (Selby, 1993). Both compressive and tensile stresses work to fracture rock, with fracture patterns commonly reflecting the source, magnitude, and direction of stress applied to the rock. Foliation or bedding can create weaknesses in rock that may eventually become fractures.

We consider fractures on scales up to that of a landscape (up to 10^6 m), but not continental or global scales. Although there is strong evidence that continental-scale lineaments do impact topography (e.g. rift zones creating grabens), it is difficult to distinguish whether such lineaments are caused by fractures (openings or distinct weaknesses in rocks, O'Leary *et al.,* 1976) or simply folding. We consider timescales from days to millions of years. As a broad approximation, these timescales correspond directly to spatial scales in terms of geomorphic process (i.e. geomorphic processes occurring on landscape scales generally do not occur over a matter of days, with the exception of catastrophic events such as volcanic eruptions or tsunamis), and we categorize the influences of joints on geomorphic processes using these approximate scales.

Review of the Influence of Fractures on Geomorphic Processes and Forms

We distinguish three categories of how the characteristics of fractures influence geomorphic processes and forms. First, the spacing and orientation of fractures exert a strong control on erosion rate and style. More densely fractured rock, for example, generally erodes faster than sparsely fractured rock (Dühnforth *et al.,* 2010; Becker *et al.,* 2014), and the spacing of fractures is a first-order control on the dominance of plucking versus abrasion in fluvial bedrock incision (Whipple *et al.,* 2000a). Second, fractures commonly bound landforms observed in the field, and there is a direct connection between erosion rate and style and the shape of landforms bound by fractures (e.g. Hancock *et al.,* 1998). Finally, variation in erosion rates across the landscape can influence the rate and spatial distribution of fracture propagation. In doing so, erosion mediated by fractures can cause either a self-reinforcing, positive feedback or a self-mitigating, negative feedback on erosion rate.

This section reviews our understanding of the impacts of fractures on geomorphology. Each of the aforementioned three sections is organized by spatial and corresponding temporal scale. The landscape scale refers to broad processes acting over 10^3–10^6 m and 10^4–10^7 years. The hillslope and valley scales refer to processes acting over 10^2–10^4 m and 10^{-1}–10^4 years. Finally, the reach and outcrop scales refer to processes acting over 10^{-3}–10^2 m and 10^{-2}–10^3 years. These distinctions are purposefully approximate and overlapping, as many processes span multiple scales. However, this scheme helps to organize processes in a comprehensible way to enable comparison and eventual synthesis.

Relationships between fracture geometry and the style and rate of erosion

Across scales and domains, more densely fractured rocks erode more easily than massive rocks. Fracturing controls the style of erosion, and the removal of fracture-bound blocks is generally more efficient than abrasion or corrosion in all geomorphic domains (Selby, 1982; Whipple *et al.,* 2000a; Dühnforth *et al.,* 2010; Naylor and Stephenson, 2010). Fracture spacing, orientation, and variability (anisotropy) in those metrics should exert a strong control on erosion rates. We use the term fracture geometry to refer to the spacing between fractures, the orientation of fractures that bound blocks, and the anisotropy of spacing and orientation in three-dimensional space. Figure 1 illustrates the processes explained later.

Landscape scale fracture influences on erosion rate and style

At the landscape scale, Molnar *et al.* (2007) suggest that tectonic stress fracturing rock is the dominant control on erosion rate across the landscape by regulating the susceptibility of rock to erosive force (Figure 1a). Tectonics can be tied numerically to erosional patterns on Earth's surface via a stress–strain framework that highlights the importance of regional weakening of rock by fracturing (Koons *et al.,* 2012). Fractures induced by tectonic stress increase bedrock surface area susceptible to weathering and the erosive effects of vegetation (e.g. Aich and Gross, 2008). By bounding blocks that can then be detached from hillslopes, fractures reduce and set the initial size of sediment supplied to hillsides, glaciers, and rivers (Sklar *et al.,* 2017; DiBiase *et al.,* 2018). By delineating zones of weaker material, fractures focus erosion across the landscape, resulting in incised gorges that follow fracture patterns (Pelletier *et al.,* 2009).

Rock erodibility is generally assumed to scale directly with fracture density. Indeed, both direct measures and proxies of erosion rates in fluvial systems indicate that erosion rates are maximized in areas of more densely spaced fractures (Figure 1b; Kirby and Ouimet, 2011; Tressler, 2011; Kirby and Whipple, 2012). In the Colorado River basin, more densely fractured rock generally exhibits lower channel steepness (a

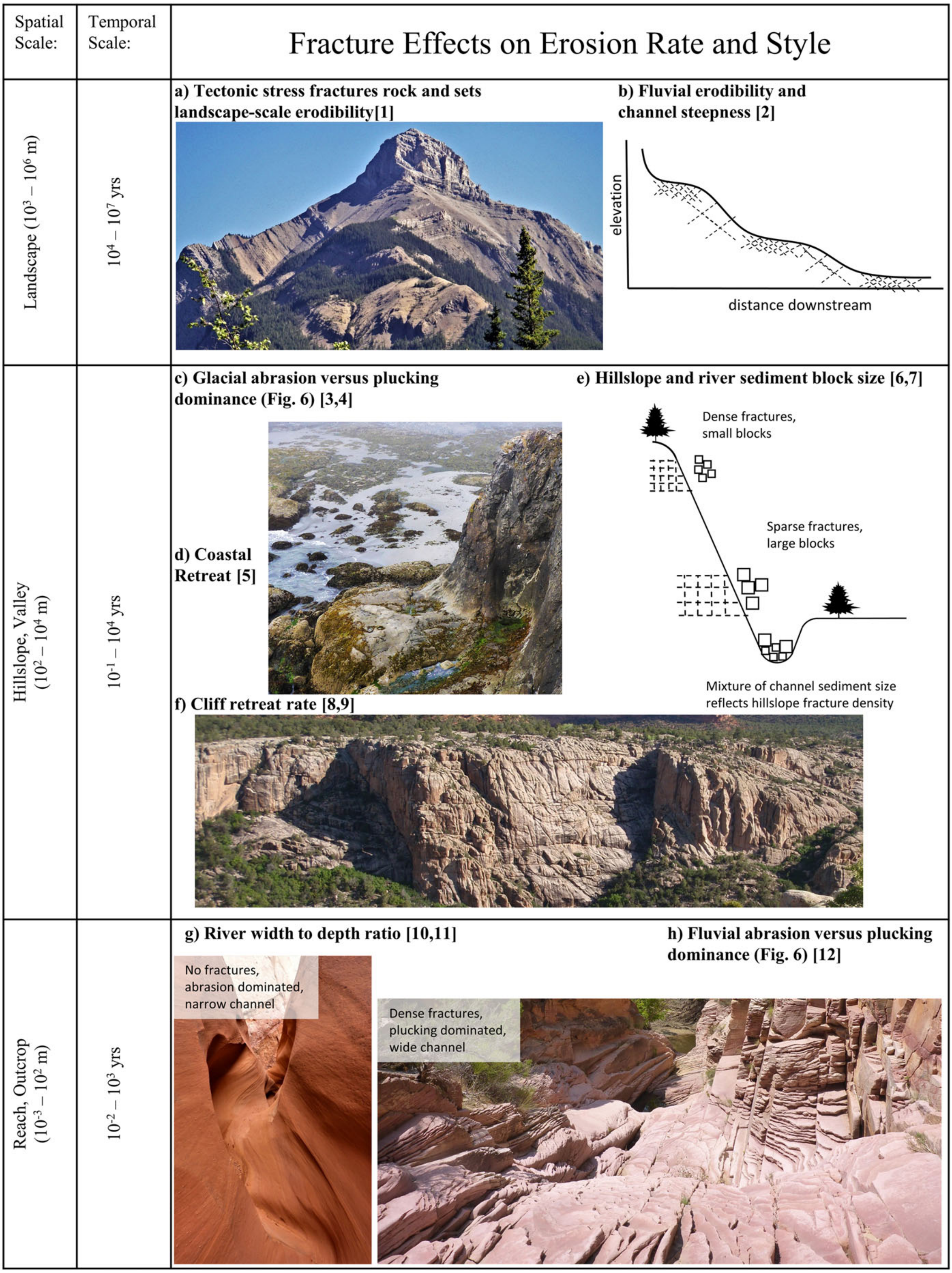

Figure 1. Summary of fracture effects on erosion rate and style, reviewed in the text, organized by spatial and temporal scale. Line drawings depict the effects in a simplified manner, photographs illustrate examples, and we provide relevant informative references for each topic. Fractures are represented by dashed lines, while solid lines represent surfaces. For illustrations of Figures 1c and 1h, please see Figure 6. References: [1] Molnar *et al.*, 2007; [2] Kirby and Whipple, 2012; [3] Krabbendam and Glasser, 2011; [4] Crompton *et al.*, 2018; [5] Naylor and Stephenson, 2010; [6] Sklar *et al.*, 2017; [7] DiBiase *et al.*, 2018; [8] Selby, 1982; [9] Moore *et al.*, 2009; [10] Wohl, 2008; [11] Johnson and Finnegan, 2015; [12] Whipple *et al.*, 2000a. [Colour figure can be viewed at wileyonlinelibrary.com]

proxy for erosion rate; Tressler, 2011; Kirby and Whipple, 2012). However, it is worth noting that this relationship is not well-studied at the landscape scale, and recent work has indicated that although fractures weaken rock and may help set its overall resistance to erosion, other factors such as tensile strength can mask the impacts of fracturing in some systems (Bursztyn *et al.,* 2015).

Glacial erosion rates are strongly linked to fracture density at the landscape scale. Becker *et al.* (2014) show that areas of densely fractured rock in Tuolumne Meadows, USA exhibit low, flat surfaces, in contrast to the more sparsely fractured rock that forms high relief cliff faces and domes. They attribute this contrast to the dominance of glacial quarrying in densely fractured regions versus abrasion in sparsely fractured regions.

Fracture geometry controls on glacial, coastal, and hillslope erosion rates and styles

At the valley and hillslope scale, fracture spacing controls the dominance of plucking versus abrasion in glacial erosion (Figure 1c). As plucking is generally more efficient than abrasion, erosion style acts as a threshold control on erosion rate. Early investigators working in dominantly granitic, exfoliated terrains noted that glacial erosion in fractured rocks is more effective than erosion in massive rocks (Matthes, 1930; Jahns, 1943). These early studies used the presence or lack of exfoliation sheets and the steepness of lee sides of large glacial landforms to infer relative erosion rates. Outside of granitic terrain, investigators noted enhanced glacial incision in densely jointed sedimentary rocks (Crosby, 1945). Building on observations of landforms, Olyphant (1981) found a nonlinear inverse relationship between estimated glacial erosion rate and average joint spacing, indicating that more closely spaced joints erode much faster than more widely spaced joints.

Following statistical evidence of the mechanism by which fractures influence glacial erosion rates, Iverson (1991) developed a numerical model to explore subglacial bedrock erosion. This model yielded new insights regarding the relationship between water in cavities downstream of quarried steps and upstream fracture growth, highlighting the importance of vertical fractures and plucking in generating a stepped profile that enabled further erosion. Building on Iverson's model (1991, Hallet (1996) developed an analytical model of glacial quarrying, which suggested that not only fracturing, but continued fracture growth, is essential to the quarrying process and high glacial erosion rates. Importantly, the model suggested that even in relatively massive rock with only minor fracturing, glacially-mediated fracture-growth could enable quarrying. Iverson (2012) recently developed a more holistic model to describe quarrying that highlights the importance of variability in fracture-mediated bedrock strength in determining the nonlinearity of the relationship between erosion rate and glacier sliding speed. In glacial settings, fracture generation by glacial stresses and erosion likely plays a dominant role in weakening bedrock (Leith *et al.,* 2014b). However, glaciers also exploit pre-existing fractures in bedrock, which in some cases can be the dominant fractures bounding plucked blocks (Hooyer *et al.,* 2012).

Field evidence to quantitatively support the importance of fracture geometry on glacial erosion rates will help to evaluate the hypotheses raised by numerical modeling, but this is sparse. In recent years, cosmogenic radionuclide dating has allowed a more quantitative evaluation of the impacts of fracture spacing on glacial erosion rates: Dühnforth *et al.* (2010) found that more densely fractured sites in Yosemite National Park, USA exhibited higher erosion rates, as suggested by beryllium-10 (^{10}Be) exposure ages. Fracture orientation, in addition to spacing, is interpreted to influence the rate of glacial erosion by determining the dominance of plucking versus abrasion. By simplifying bedding dip as being either in the direction of ice flow or opposed to it, investigators have used field evidence to infer that dip direction controls the prevalence of plucking versus abrasion in glacial erosion (Kelly *et al.,* 2014; Lane *et al.,* 2015). However, the effects of more complex orientation variability beyond bedding dip on glacial erosion process dominance or erosion rate have yet to be understood. Indirect evidence relating fracture spacing to glacial erosion rate also comes from Crompton *et al.* (2018), suggesting that glacial surging (dramatic changes in ice flow velocity that may regulate erosion rate; Smith, 1990; Humphrey and Raymond, 1994) may be controlled by fracture spacing influences on till dynamics on the bed.

In the coastal domain, fracturing weakens rock and changes the style of coastal retreat (Figure 1d). More densely fractured rocks can enable coastal retreat rates twice that of less fractured rock (Barbosa *et al.,* 1999). Similarly, shore platforms in more densely jointed rocks are lowered to a greater extent than nearby, more sparsely jointed platforms (Kennedy and Dickson, 2006). Naylor and Stephenson (2010) performed a detailed investigation of fractured bedrock exposed on coastlines. They found that the spacing of bedding planes controlled the ability of waves to erode portions of coastal cliff faces. More closely spaced joint sets permitted enhanced erosion of certain sedimentary beds, and the orientation of joint sets and their continuity in space controls their resistance to erosion. This is a prime example of how anisotropy in joint spacing and orientation plays an important role in determining erosion rate and style.

Sediment delivery to rivers and glaciers may be set by fracture spacing, orientation, and anisotropy (Figure 1e; Sklar *et al.,* 2017; DiBiase *et al.,* 2018). This sediment acts as tools (enabling erosion by abrasion) and cover (enabling alluviation and preventing incision into bedrock) in fluvial erosion (Sklar and Dietrich, 2004), thus influencing erosion rates. The link between fracture spacing and the eventual size of sediment delivered to rivers has yet to be fully understood due to the myriad of breakdown processes that occur between the production of sediment from bedrock, its transport downslope, and its eventual deposition in the channel. However, a case study comparing two sites with differing fracture density shows that fracture density can set channel erodibility and landscape relief structure by setting the size of sediment delivered to channels (DiBiase *et al.,* 2018). Numerical modeling also indicates that sediment delivery may play a strong role in linking fracture geometry to landscape evolution (Roy *et al.,* 2016b).

More densely fractured hillslopes are inherently less stable (Figure 1f; Clarke and Burbank, 2011; Loye *et al.,* 2012; Selby, 1982) and experience higher erosion rates than hillsides in massive rock. Although fracture geometry controls the erodibility of hillslopes and the rates at which they erode (Selby, 1982, 1993), the literature generally focuses on how fractures control the location, orientation, and size of mass movements, and are hence treated in more detail later.

Fracture geometry controls on fluvial erosion rate and style

At the reach scale, fractures influence erosion rate dominantly by controlling the spatial orientation of fluvial erosion (vertical incision versus lateral widening), and determining whether plucking or abrasion dominate the erosion of bedrock rivers (Figures 1g and 1h). Work examining the density of fractures in relationship to bedrock channel morphology has shown how fracture density exerts a strong control on channel width, with more densely fractured rock exhibiting wider valleys (Ehlen and Wohl, 2002; Wohl, 2008). Multiple studies have documented the process of subaerial weathering leading to densely fractured sedimentary rocks (slaking) that enable significant erosion at channel margins, leading to widening and the potential for strath terrace formation (Montgomery, 2004; Johnson and Finnegan, 2015; Schanz and Montgomery, 2016). This is a prime example of surface fracturing creating anisotropy in fracture density and erodibility, leading to non-uniform erosion rates within a channel.

Rivers and glaciers exploit fractures to erode bedrock via plucking. Over the last two decades, much of the research into plucking erosion has used physical and numerical modeling to determine thresholds for block entrainment from the bed. Four mechanisms of entrainment have been examined: sliding (Hancock *et al.,* 1998; Dubinski and Wohl, 2013), vertical entrainment (Coleman *et al.,* 2003), pivoting about an upstream-facing step following vertical entrainment (Wende, 1999; Fujioka *et al.,* 2015), and toppling (Lamb and Dietrich, 2009).

Vertical entrainment is likely the initial entrainment mechanism that enables the pivoting of tabular blocks about upstream-facing steps (Wende, 1999). However, it is extremely rare to observe cavities in the bed bound on all sides by rock that would represent the space left by a purely vertically entrained block (i.e. with no pivoting), and pure vertical entrainment requires block protrusion to an extent not observed in natural channels (Coleman *et al.,* 2003; Lamb *et al.,* 2015), indicating that pure vertical entrainment without pivoting likely does not occur in natural channels. Vertical entrainment and pivoting about an upstream-facing step likely occurs in streams eroding bedded lithologies that dip downstream, based on observations of upstream-facing steps with tabular, block-shaped voids that follow fractures oriented perpendicular to flow (e.g. Figure 2). Wende (1999) suggests a critical flow velocity entrainment threshold for blocks resting against an immobile upstream-facing step on their downstream side. This threshold is mainly a function of the block height and top surface area, although it neglects wall friction. More tabular blocks with large top surface areas relative to their height are predicted to be more easily vertically entrained and then flipped or pivoted as they move downstream. This theoretical prediction was confirmed by flume experiments that showed flipping to be a viable entrainment mechanism, although, depending on the height of the upstream-facing step, blocks may not be fully flipped after entrainment (Wende, 1999). In contrast to the vertical entrainment synthesized by Lamb *et al.* (2015), this type of entrainment requires a free surface on the upstream side of the block. However, this shows that vertical entrainment, at least when it precedes pivoting about an upstream-facing step, is likely an important mechanism of entraining blocks in fractured channels.

Both sliding and toppling entrainment are strongly dependent on the ratio of block dimensions, primarily height and length (Lamb and Dietrich, 2009; Dubinski and Wohl, 2013; Lamb *et al.,* 2015). This indicates that fracture spacing and spacing anisotropy (deviation from cuboid fracture systems) may exert strong controls on entrainment rates. Most existing work focuses on cuboid systems: only recently has experimental work examined non-cuboid fracture systems (George *et al.,* 2015) and concluded that block orientation relative to the flow, determined by fracture geometry, exerts a strong control on the entrainment threshold.

Field observations demonstrate that plucking can occur in modes similar to those simulated in flume settings (Lamb and Fonstad, 2010; Anton *et al.,* 2015), and that plucking of fractured rock is likely the only way to explain high erosion rates in rivers. Natural channels display strong spatial variability in plucking rates, associated with the migration of knickpoints (Miller, 1991; Seidl *et al.,* 1994; Lima and Binda, 2013). This spatial and temporal variability in the rate of erosion resulting from plucking makes it very difficult to accurately model channel evolution due to plucking. Despite this, numerical modeling has shown success in simulating decadal-scale evolution of a bedrock channel (Chatanantavet and Parker, 2009, 2011). This model uses a conservation of mass approach by conceptualizing plucking as a process of stripping off particles produced by weathering and fracture propagation. Faster fracture propagation and the lack of sediment cover enhance plucking in this model. Despite not explicitly treating fracture geometry, this model accurately simulates knickpoint formation and development. This indicates that a detailed mechanistic understanding of plucking may not be necessary for understanding channel evolution on timescales of decades.

Figure 2. Example of upstream-facing steps in a limestone bedrock river, Marienbergbach, Austria. Flow is from bottom right to top left. Red lines delineate major downstream-dipping joints (formed by bedding planes) that bound the downstream faces of steps. These bedding plane joints, along with other fractures, create upstream-facing steps. Plucking may occur by the flipping or vertical pivoting of tabular blocks from the bed that can rotate around the lips of such upstream-facing steps as per Wende (1999). [Colour figure can be viewed at wileyonlinelibrary.com]

However, to add complexity, it is important to note that entrainment only partially determines erosion rates due to plucking. Transport of plucked blocks, which act as alluvium after entrainment, and the propagation of fractures (see later) are necessary to prevent alluviation of the bed and thus enable erosion. Lamb *et al.* (2015) highlight the lack of observational data to examine this question, although Chatanantavet and Parker (2011) have developed a model that can accommodate variability in alluviation as a function of bed sediment and fracture propagation, which could be used as a starting point for further field testing. Using a critical dimensionless shear stress formulation to describe entrainment thresholds under the aforementioned mechanisms of entrainment, Lamb *et al.* (2015) point out that sliding-dominated and especially toppling-dominated reaches are likely transport limited. The distribution of sediment in the form of blocks in fractured bedrock rivers, especially at the base of toppling-dominated knickpoints, seems to support this observation. Additionally, a transport-limited model performs well in predicting channel development in a well-jointed substrate (Lamb and Fonstad, 2010). However, the abundance of sustained bedrock reaches that exhibit fracture-bound voids and plucking dominance, and that are devoid of sediment, indicates that entrainment rate likely limits erosion rates in many systems. It is important to note that analytical models of plucking entrainment are generally based on cuboid fracture sets with two fracture sets oriented normal to flow and one oriented parallel to flow. This is an idealization that is rarely an exact description of natural systems, and it is important to note that non-cuboid (even subcuboid) fracture orientations are significantly more complex.

Determining thresholds for erosion process dominance in bedrock rivers. Bedrock river evolution is largely determined by the dominance of plucking versus abrasion processes (e.g. Figures 1g and 1h). Because bedrock rivers fundamentally regulate landscape evolution, it is imperative to understand the conditions that determine erosion process dominance. Although field observations have indicated that bedrock channels with closely spaced fractures are dominated by plucking erosion and exhibit higher erosion rates than massive, abrasion-dominated channels (Whipple *et al.,* 2000a), a threshold fracture spacing that enables plucking has yet to be identified. The question of whether plucking or abrasion accounts for the majority of the erosion in a reach is deceptively difficult to answer. Many investigators have used the morphology of the bed as an indicator of the relative efficiency of plucking versus abrasion (Tinkler, 1993; Hancock *et al.,* 1998; Whipple *et al.,* 2000b; Beer *et al.,* 2016), while acknowledging (Tinkler, 1993; Hartshorn, 2002) and even directly observing evidence (Beer *et al.,* 2016) that plucking is a much more episodic style of erosion than abrasion. Even in sculpted channels, where abrasion seems to dominate, plucking may still remove more material over long timescales (Beer *et al.,* 2016).

The presence of sculpted bedforms only indicates that abrasion has continued long enough to sculpt the bed; even a few millimeters of erosion, potentially accomplished over the course of a few years (based on observed abrasion rates on the order of 1 to 5 mm a^{-1} in natural channels; Hancock *et al.,* 1998; Whipple *et al.,* 2000a; Beer *et al.,* 2016), can obscure more sharply angled plucked forms. If the time between plucking events is greater than the time needed to smooth the bedrock, then the presence of sculpted forms in a channel cannot be a reliable indicator of process dominance. The detailed measurements of a bedrock gorge performed by Beer *et al.* (2016) over the course of two years exemplify this observational difficulty by showing that a single and likely infrequently occurring plucking event dramatically exceeded rates of erosion by abrasion, even in dominantly sculpted and massive bedrock. A sculpted bed may simply be exhibiting a long 'waiting time' (Hancock *et al.,* 1998) between plucking events. An exception to this is when the bed substrate is entirely massive and no fracture-bound clasts are evident in bed material: abrasion must dominate in conditions with no fractures to create blocks and without evidence that macroabrasion (breaking of bedrock into blocks by the impact of large clasts) is sufficient to fracture rock into blocks for plucking (e.g. Coyote Creek, Utah, Wohl *et al.,* 1999).

Although the shape of canyon walls generally preserves evidence of erosive style in a bedrock channel (e.g. asymmetric wall slopes may indicate lateral migration), valley wall morphology may not indicate process dominance. Shear stress decreases with height above the bed, and abrasion may dominate high off the bed in a confined channel (although subaerial weathering may produce smaller and more easily detached blocks higher off the bed, counteracting this; Shobe *et al.,* 2017). As the channel incises, abrasion may be the last process to fluvially erode the walls before the channel incises sufficiently deeply to stop shaping the walls above a certain height from the bed. This would result in smoothed walls that, although they could have been exposed by plucking or abrasion incision, only reflect the last erosive process, which may have been abrasion.

That said, a similar conundrum may not apply to inferring the dominance of plucking from channel form. Plucking likely dominates in channels that are obviously blocky and exhibit fracture-bound, concave forms (cavities left from plucked blocks; e.g. Figure 2). Plucking is likely more episodic (due to requiring high shear stresses to move blocks) and effective (due to removing large blocks of material over short timescales) than abrasion, which can be assumed to occur more consistently through time in systems that are not entirely devoid of sediment (Hancock *et al.,* 1998; Whipple *et al.,* 2000a; Sklar and Dietrich, 2004). As such, for a channel bed to persistently exhibit sharp, fracture-bound angles and plucked cavities, plucking must outpace abrasion, even though it may not occur as often.

Because plucking likely is much more effective than abrasion, and because it can occur even in otherwise massive rocks via fracturing due to macroabrasion (Whipple *et al.,* 2000a; Whipple, 2004), plucking in some form probably should be assumed to be the default mode of eroding bedrock in the absence of definitive evidence that abrasion dominates. In terms of field observation, such definitive evidence may come from the lack of plucked forms on the bed, the lack of fracture-bound clasts in bed material, and well-developed sculpted forms in the absence of strongly expressed fractures or evidence of plucking.

Temporal and spatial scale can also determine process dominance. In reconciling low, short-term, abrasion-related erosion rates with higher long-term erosion rates from strath terraces on the Indus River in Pakistan, Hancock *et al.* (1998) note that extremely infrequent plucking events could have eroded significant amounts of material. Over short timescales on sculpted beds, abrasion almost certainly dominates. However, over longer timescales, potentially on both sculpted and blocky beds, plucking may dominate. Spatially, plucking may only occur infrequently and across small portions of the bed, similarly to abrasion, which varies strongly in space depending on bedform orientation (Hancock *et al.,* 1998; Beer *et al.,* 2016). Accurately determining the conditions that lead to the dominance of episodic plucking processes over more continuous abrasion processes is essential for understanding and predicting the evolution of bedrock rivers and landscapes.

Fracture controls on the shape, orientation, and location of landforms and erosion

Some of the earliest investigations into the impacts of fractures on the development of landscapes focused on spatial correlations between fractures and erosional forms (Hobbs, 1905; Bryan, 1914). Fractures control the shape, orientation, and location of landforms by two mechanisms. First, because fractures increase the erodibility of the landscape, they tend to focus erosion and create incisional features. Second, fractures bound eroded blocks. As glacial plucking, fluvial plucking, or hillslope failure remove blocks, they leave a cavity that defines the micro- to meso-scale morphology of the eroded landscape, commonly bound by one or more fractures. These two mechanisms work together on multiple and overlapping temporal and spatial scales to produce a landscape that is typically defined by the underlying fracture network. Figure 3 illustrates the processes explained later.

Fracture controls on the orientation and elevational distribution of topography

At the landscape scale, one of the most noticeable impacts of fracturing on the landscape is the correlation between fracture orientation and stream planform orientation (Figure 3a). This correlation has been noted in a wide variety of landscapes, including relatively tectonically quiescent, climatically wet limestone landscapes in the north-eastern United States (Hobbs, 1905; Sheldon, 1912; Cole, 1930); arid sandstone and metamorphic landscapes of the south-western United States (Bryan, 1914; Pelletier *et al.,* 2009); glaciated sedimentary landscapes of Greenland (Pessl Jr, 1962); subhumid sandstone landscapes in Australia (Baker and Pickup, 1987); metamorphic rocks in the Southern Alps of New Zealand (Hanson *et al.,* 1990); sedimentary rocks of central India (Kale *et al.,* 1996); granitic and gneissic terrain of South Africa (Tooth and McCarthy, 2004); and granitic terrains of the US Sierra Nevada (Ericson *et al.,* 2005). The ubiquity of this correlation has led many researchers to hypothesize that underlying fractures control the distribution of erosion on the landscape, with the result that valleys tend to follow fractures.

However, as landscape evolution modeling has taken a leading role in augmenting our understanding of erosional processes, researchers have been able to draw mechanistic links to bring causation to the aforementioned correlation between fractures and valley orientation. One of the major difficulties in this correlation is that, although streams generally follow fractures, not all fractures are exploited by these streams. Pelletier *et al.* (2009) address this difficulty using numerical modeling to explore fracture-controlled drainages in metamorphic core complexes of Arizona in the United States. They found that tectonic tilting of the landscape was likely responsible for the preferential exploitation of certain joint sets across the landscape, producing the drainage pattern observed today. In contrast, Ericson *et al.* (2005) found that glacial erosion could force what are now fluvially dominated streams to follow major joints that do not follow the range-wide slope. Earlier modeling of glacial erosion shows that contrasts in rock erodibility determined by fracture geometry may strongly influence glacial valley form and the lateral distribution of erosion across the valley (Harbor, 1995). This indicates that widespread fracture sets can similarly influence both glacial and fluvial erosion. Focusing on fluvial erosion, Roy *et al.* (2015) use numerical modeling of fault-weakened zones and show that a sufficient erodibility contrast (potentially due to variability in fracture density) between a weakened zone and surrounding rock is necessary for that weakened zone to control drainage network development. The orientation of the weak zone also controls the development of valley walls as the river incises.

Fracture controls on the spatial distribution of erosion are not limited to fluvial systems. Becker *et al.* (2014) found that extremely densely fractured zones caused preferential glacial quarrying in Tuolumne Meadows, where topographic highs correspond to areas lacking bands of fractured rock and lows correspond to areas that exhibit these fractured zones (Figure 3b). This provides direct evidence for Molnar *et al.*'s (2007) suggestion that the mechanism by which tectonics most influences the landscape is by fracturing rock and focusing erosion. More densely fractured rock is more easily eroded, leaving high elevation features in areas of sparse fracturing. For example, topographic variations in granitic uplands (e.g. tors) correspond to spatial variations in fracture spacing. Fracture spacing sets the size and morphology of tor blocks produced by weathering (Gerrard, 1976; Ehlen, 1992).

Also in the glacial domain, researchers have long recognized that fjords tend to follow the orientation of regional fracture systems (Figure 3c; Holtedahl, 1967; Nesje and Whillans, 1994; Glasser and Ghiglione, 2009). Fractures enable glaciers to preferentially erode certain parts of the landscape repeatedly across glacial cycles, and have been proposed to be the dominant control on fjord development, as opposed to internal glacial dynamics (Glasser and Ghiglione, 2009). Although glacial erosion that creates fjords appears to simply follow fractures at a broad scale, fractures likely influence glacial erosion rates by allowing for rapid removal of fracture bound blocks (see earlier). Evidence for this comes from the morphology of fjord valley floors, which exhibit knickpoints bound by fractures (Holtedahl, 1967).

Fracture controls on the morphology of hillslopes and valleys

Glaciers carve landforms on the scale of hillslopes and valleys that are commonly defined more by fracture orientation and spacing than by glacial dynamics (Figure 3d). Examining glacial valley floors using numerical modeling, Anderson (2014) shows that because fracture spacing determines the size of blocks able to be quarried on the bed, in turn controlling the dominance of abrasion versus quarrying, steps with a wavelength determined by variations in fracture spacing form periodically in the evolution of a glacial valley. Glacial landforms are commonly bound by dominant joint sets in a region (Matthes, 1930; Gordon, 1981; Rastas and Seppala, 1981; Olvmo and Johansson, 2002). Roche moutonées, commonly cited as indicators of ice flow direction, have been observed to follow joint sets rather than ice flow direction (Gordon, 1981). Rastas and Seppala (1981) show that the spacing and size of roche moutonées follow the spacing of dominant fractures, providing an example of how underlying fracture geometry exerts the dominant control on the dimensions of a landscape.

Hillslope morphology, and the spatial distribution of mass movements that control hillslope evolution in steep terrain, are determined by the spacing, orientation, and geometric anisotropy of fractures (Figure 3e; Selby, 1982, 1993). In general, slopes with more closely spaced fractures, and those with fractures dipping out of the slope, accommodate sliding failure more easily. Indeed, Moore *et al.* (2009) show that fracture orientation dominates over other controls on long-term cliff retreat rates in the Sierra Nevada. The location of avalanches and hillslope failures typically correlates with joint sets (Figure 3f; Butler and Walsh, 1990; Cruden, 2003; Braathen *et al.,* 2004; Loye *et al.,* 2012). Mountain tops and bedrock slopes exhibit morphologies that are a direct result of rock strength and angle of bedding planes or joint sets that form planes of weakness and eventual failure (Selby, 1982; Cruden, 2003; Braathen *et al.,* 2004). By setting the size of blocks produced by weathering

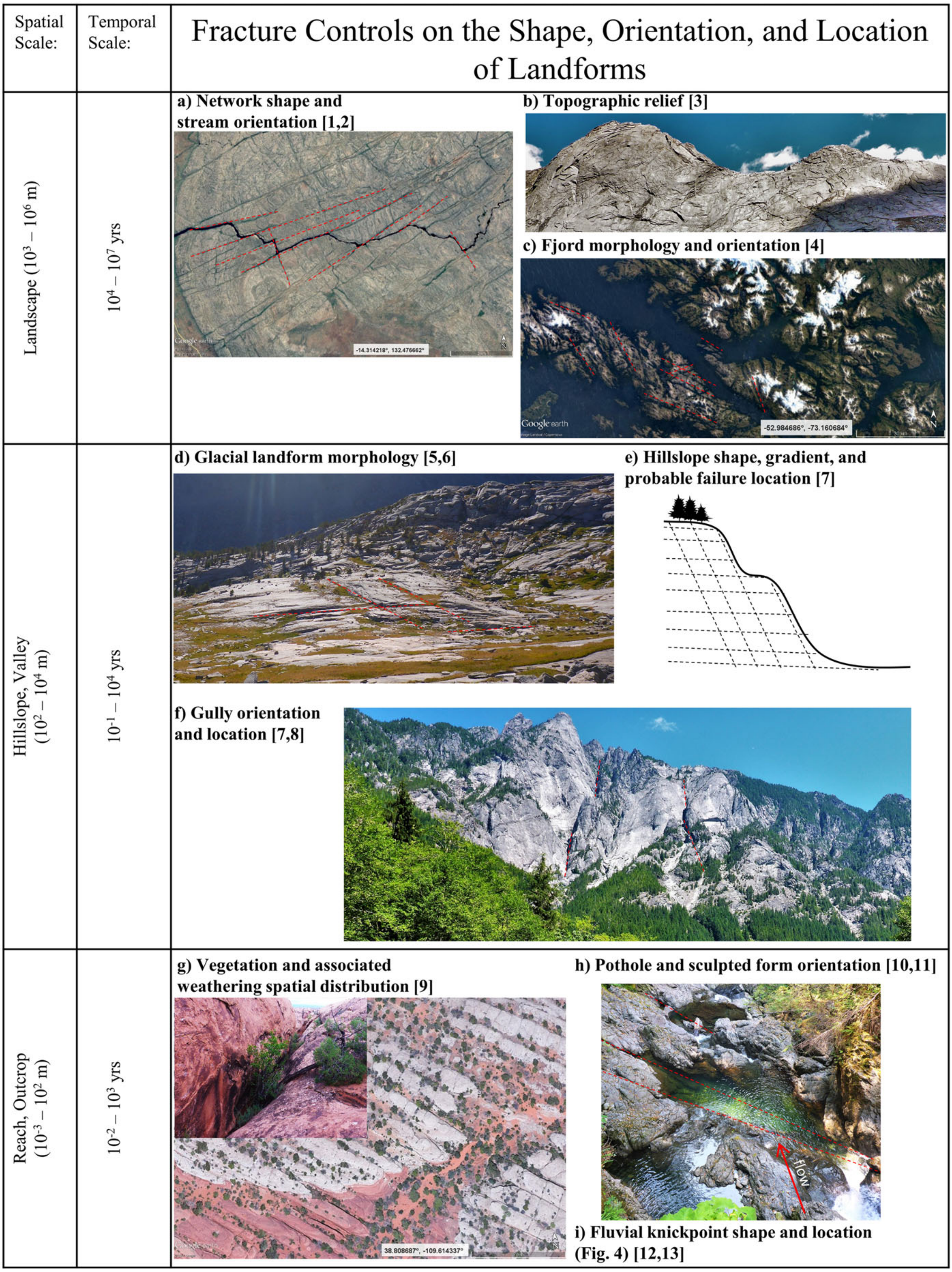

Figure 3. Summary of fracture controls on the shape, orientation, and location of landforms, reviewed in the text, organized by spatial and temporal scale. Line drawings depict the effects in a simplified manner, photographs illustrate examples, and we provide relevant informative references for each topic. Dashed lines represent fractures, while solid lines represent surfaces. Arrows indicate flow direction. References: [1] Pelletier *et al.,* 2009; [2] Tooth and McCarthy, 2004; [3] Becker *et al.,* 2014; [4] Glasser and Ghiglione, 2009; [5] Rastas and Seppala, 1981; [6] Anderson, 2014; [7] Loye *et al.,* 2012; [8] Butler and Walsh, 1990; [9] Aich and Gross, 2008; [10] Velázquez *et al.,* 2016; [11] Ortega-Becerril *et al.*, 2016; [12] Bryan, 1914; [13] Lamb and Dietrich, 2009. [Colour figure can be viewed at wileyonlinelibrary.com]

and erosion, fractures can set the slope of talus fields on hillslopes (Bryan, 1914; Caine, 1967). A detailed analysis of fracture geometry can yield insights into likely failure mechanisms and eventual post-landslide morphology (Brideau *et al.,* 2009). Loye *et al.* (2012) present a detailed look at the mechanism by which fractures influence the location of hillslope failure, showing that not simply fracture orientation, but instead the orientation of maximum joint frequency, can set the bulk strength of the hillslope. This implies a strong role of fracture anisotropy on hillslope failure probability.

Fractures can control the distribution of vegetation across bedrock, especially in arid landscapes (Figure 3g). Vegetation exploits fractures in bedrock as zones of enhanced soil development, water retention, and weathering rate, harboring substrate, water, and nutrients for plants, but only where soil does not thickly mantle bedrock (Burkhardt and Tisdale, 1969; Loope, 1977; Yair and Danin, 1980). In arid landscapes, fracture patterns can actually be identified via aerial photography by tracing lines of vegetation exploiting those fractures (e.g. Aich and Gross, 2008). The result of this enhanced vegetation growth in fractures is seen in the physical effects of roots on bedrock, with roots exerting force due to both swelling and above-ground motion (Strahler, 1952; Roering et al., 2003, 2010), and chemical weathering feedbacks that influence fracture propagation (see later). Tree throw erodes bedrock by root exploitation of fractures and can transport significant amounts of sediment downslope. As trees fall, they transport material downslope. If trees are rooted into bedrock, they break off bedrock blocks and transport them downslope (Gabet *et al.,* 2003; Gabet and Mudd, 2010).

Fracture controls on the reach scale morphology of rivers

At the reach scale, individual channels in a bedrock river can exploit joints to produce anabranching planforms (Kale *et al.,* 1996; van Niekerk *et al.,* 1999; Tooth and McCarthy, 2004). In these cases, rivers erode preferentially along fractures. Tooth and McCarthy (2004) note that both joints and foliation direct the abrasion of bedrock, creating sculpted, multi-thread channels. However, plucking also appears to be capable of producing such a planform (Kale *et al.,* 1996). Tooth and McCarthy (2004) provide a detailed synthesis of anabranching planform observations in bedrock and conclude that fracturing is likely necessary for such a planform to develop in bedrock. By providing strong heterogeneity in cross-sectional erodibility, fractures overcome the usual positive feedback between channelized flow, erosion of a thalweg, and further channelization, forming a long-lived, multi-thread planform (Tooth and McCarthy, 2004).

Similar to planform, fluvial longitudinal form can be determined by fractures. Bryan (1914, p. 133) provides an excellent example of a knickzone with near-vertical and near-horizontal surfaces (forming the longitudinal profile of the knickzone) that follow major joint sets (Figure 3i). Knickpoint or step height is commonly strongly related to bedding thickness in sedimentary rocks, and knickpoint lips typically follow oblique or perpendicular-to-flow joint sets (e.g. Miller, 1991, Figure 4). Knickpoint spacing and location have been observed to depend strongly on the longitudinal distribution of vertical joints (Phillips and Lutz, 2008). Lamb and Dietrich (2009) provide evidence for plucking by toppling on knickpoints with subvertical joints defining their faces and sufficiently deep plunge pools as a mechanism for preserving vertical faces as knickpoints retreat. Fracture orientation appears to strongly influence knickpoint morphology and inferred migration rate in multiple lithologies (Phillips and Lutz, 2008; Lima and Binda, 2013; Ortega *et al.,* 2013). However, mechanisms of knickpoint retreat in the presence of influential fracture systems are poorly understood.

Within a single reach or knickpoint, fractures commonly define the margins of bedforms, reflecting various mechanisms of plucking and concentrated abrasion. As mentioned earlier, sliding, toppling, flipping/pivoting, or vertical entrainment can remove blocks from the streambed. The cavities left from plucking create the typical morphology of the bed of a fractured bedrock river (e.g. Figure 4). Toppling has been proposed as a mechanism that can sustain larger vertical forms (Lamb and Dietrich, 2009). Flume observations have shown that sliding can similarly sustain vertical, joint-bound steps in the bed,

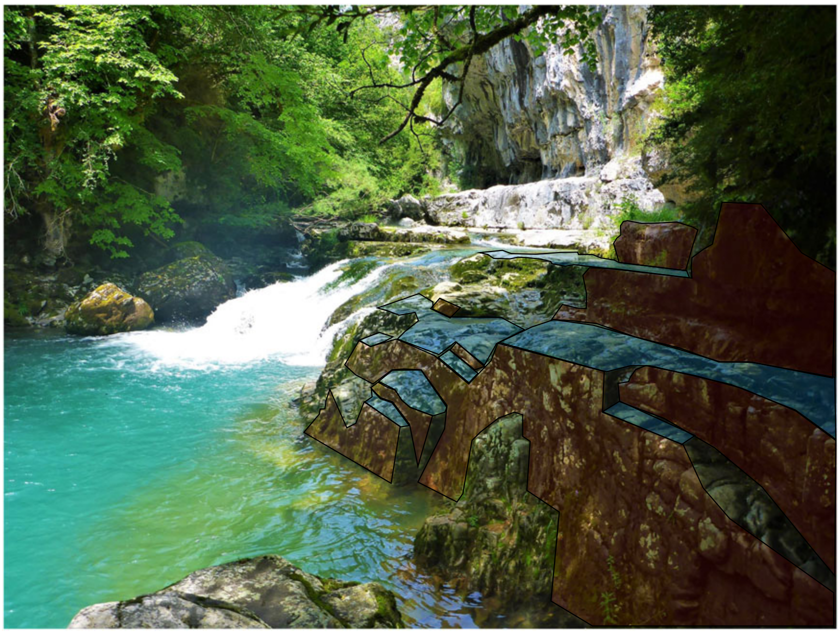

Figure 4. An example of a knickpoint oriented oblique to flow bound by sub-vertical joints on the Aso River, Spain (approximate location: 42.563125, 0.039353). Note the generally cuboid blocks and the voids left by plucking in the right foreground. Shading in the foreground highlights the planar surfaces bound by joints that set the form of the knickpoint. Red shading indicates subvertical joint-bound surfaces perpendicular to flow, and blue shading indicates subhorizontal joint-bound surfaces. [Colour figure can be viewed at wileyonlinelibrary.com]

and cross-sectional distributions of sliding rates can influence the morphology of block bedforms at knickpoint lips (Dubinski and Wohl, 2013). Vertical entrainment would likely produce block-shaped holes in the bed, although such holes are not commonly documented in real channels. As Lamb *et al.* (2015) point out, other mechanisms of plucking are more likely to dominate unless blocks protrude from the bed to a degree not commonly seen in natural rivers. Pivoting vertical entrainment about an upstream-facing step tends to produce and sustain upstream-facing steps and imbricated boulder slab bedforms in bedding-dominated bedrock rivers (e.g. Figure 2; Wende, 1999). Sedimentary bedding in particular can form fracture-bound planar surfaces, where the channel follows a single sedimentary bedding plane for some length and then moves to another sedimentary bed at a step (Miller, 1991; Richardson and Carling, 2005).

Abrasion can also exploit fractures on the bed, creating sculpted forms with a geometry that follows fracture orientation or is bound by fractures (Figure 3h). Early investigations of potholes indicated that they can exploit steeply dipping fractures in the bed (Elston, 1918). Like many other effects of fractures on geomorphology, investigation of this process has mostly been limited to observational correlations between fractures and pothole orientations, locations, and shapes (Bryan, 1920; Springer *et al.,* 2006; Ortega *et al.,* 2014). More recently, detailed geotechnical and statistical investigations of potholes seem to confirm that potholes can exploit small-aperture fractures on the bed, and that potholes correlate more strongly with fracture orientation and substrate resistance than with hydraulics (Ortega-Becerril *et al.,* 2016). Similar to glacial landforms on a much larger scale, potholes seem to be more reflective of underlying substrates than the flow of material that scours them. Other sculpted forms in bedrock channels also exhibit fracture control, especially in the case of furrows or solution pits following fractures on the bed (Richardson and Carling, 2005). Fractures that induce flow separation can act as seeds for sculpted forms such as flutes (Velázquez *et al.,* 2016). Springer *et al.* (2002) suggest that fractures on the bed and walls act to anchor sculpted forms in place, fundamentally altering their long-term evolution.

Feedbacks between erosion and fracture propagation

Feedbacks between erosion of the land surface and fracture propagation regulate how fractures influence erosion rate and style through time (e.g. Molnar, 2004). In a system with surface-generated fractures, the ratio of the rate of erosion to the rate of fracture propagation controls how bedrock erodibility may change through time, as fractures must continually form and propagate in order for block removal type erosion to continue (e.g. Hancock *et al.,* 1998; Chatanantavet and Parker, 2009). Figure 5 illustrates the processes explained here.

Fracture propagation feedbacks at the landscape and valley scales

On landscape scales, relatively widespread tectonic stresses modulated by topographic stresses on rock form and propagate fractures (Figure 5a). Topographic stress refers to gravitational stress near Earth's surface generated by relief. As relief increases, the stress exerted on ridges, hillslopes, and valley bottoms increases. Models indicate that this stress is sufficient to fracture bedrock (Miller and Dunne, 1996). Thus, as rivers erode and create relief, stress increases and rock fractures, enabling further erosion of bedrock. Although this may appear to be an inherently positive feedback, it is important to note that in accelerating the pace of relief generation via fluvial incision, this fracturing can also accelerate hillslope failure, potentially covering valley bottoms with sediment and preventing rivers from incising bedrock (Molnar, 2004). The direction and magnitude of this feedback depend on the relative rates of fluvial incision versus hillslope erosion and sediment supply, as well as the lateral stress regime induced by regional tectonics, as variation in fracture orientation may differentially favor the erosion of hillslopes versus valleys.

Comparing numerical modeling to field observations tests whether topographic stresses can be a dominant control on rock fracture patterns. Field observations of fractures from borehole (Slim *et al.,* 2015) and geophysical data (St Clair *et al.,* 2015) find that numerically modeled fractures due to topographic stresses generally follow patterns observed in the field, supporting the idea of topographically induced stresses fracturing rock and likely influencing landscape evolution.

Numerical modeling can examine the possible feedback between topographic stress fracturing and landscape evolution. Roy *et al.* (2016a) use a coupled numerical model of crustal deformation in response to fluvial incision to suggest that incision focuses stress and resulting rock damage (fracturing), resulting in erodibility contrasts that control drainage network development. Moon *et al.* (2017) model three-dimensional topographic stresses to better understand the relationship between landform orientation and tectonic stresses, finding that both the orientation and location of fracture-rich zones depend on stress orientation and topographic geometry. They suggest a framework based on compressive stress and topography that generates testable hypotheses regarding the spatial distribution (ridges versus valleys) of topographically-induced fracturing and the resulting direction of the feedback between topographic fracturing and incision rate.

Topography also influences landscape evolution via pressure-relief fracturing, or exfoliation. Pressure-relief stresses modulated by exhumation and existing topography cause widespread microcrack formation and eventual fracture propagation (Figure 5b; Leith *et al.,* 2014a). This process is best displayed in granitic lithologies, where some of the first observations of the process were made (e.g. Dale, 1923; Matthes, 1930; Jahns, 1943). As erosion removes exfoliated sheets and relieves pressure on the underlying rock, fractures form subparallel to Earth's surface. Recently, advances have been made in understanding the mechanisms of fracture propagation that occur during granite exhumation. Through detailed monitoring of exfoliating slabs, diurnal thermal stresses emerge as the most likely candidate for actual fracture propagation. These stresses have been observed to trigger slab failure and rock fall (Collins and Stock, 2016).

Fracture propagation feedbacks at the reach and outcrop scales

The rate of surface fracture propagation is dependent on the rate of exposure of bedrock. Surface fractures are generally small-scale features in terms of the depth to which they have a measurable aperture. As such, fracture propagation processes that widen fractures and/or extend fracture tips generally operate at small scales, despite their widespread effects on landscapes (e.g. frost cracking reducing the erodibility of a landscape; Marshall *et al.,* 2015). The following processes all act to exert pressure on the sides of fractures or pressure on the surface that translates to pressure within a fracture that acts to widen the fracture.

In cold, alpine landscapes, fracture propagation feedbacks occur both below glaciers and in unglaciated regions. Numerical modeling suggests that more broken rock should

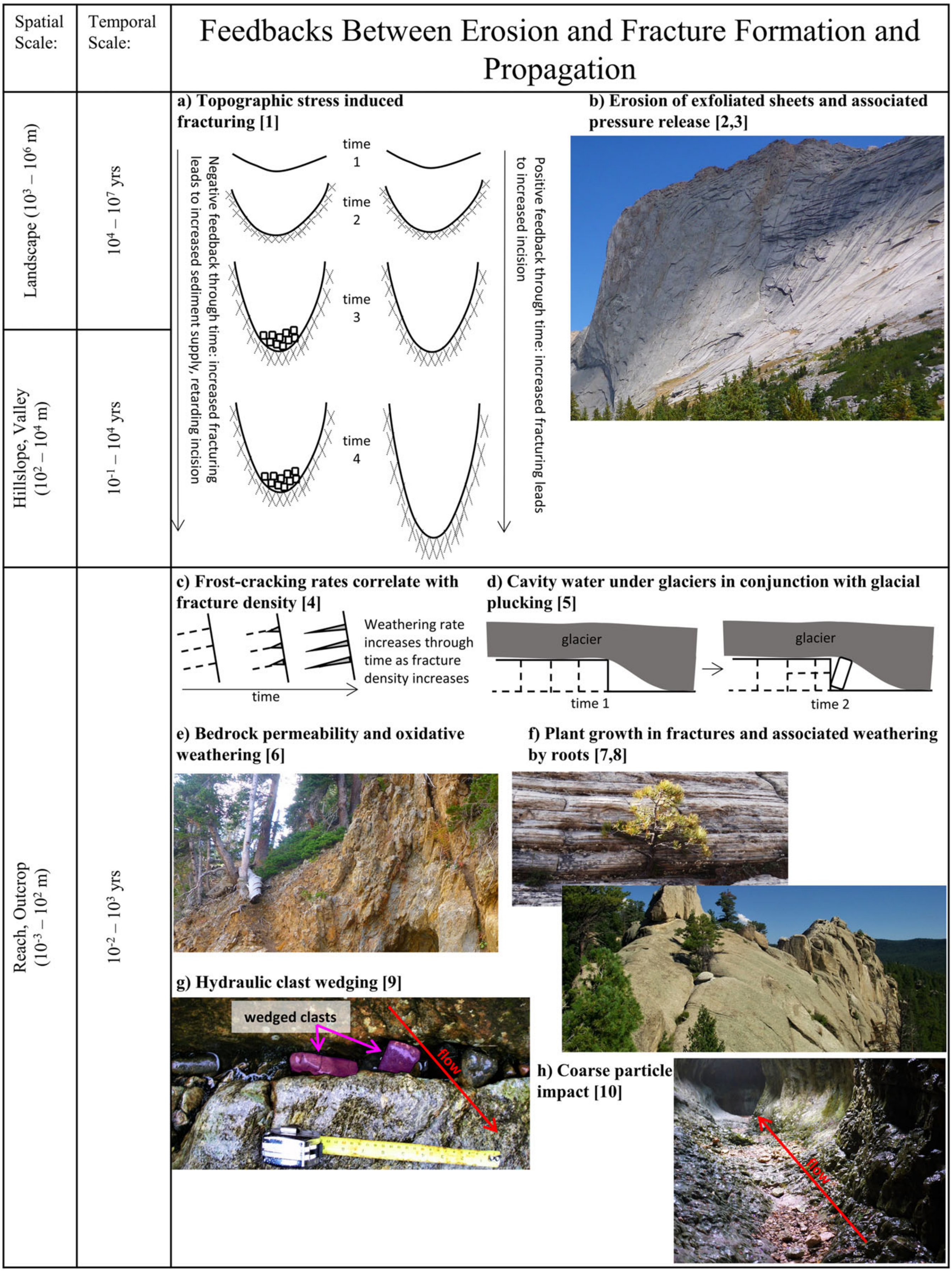

Figure 5. Summary of feedbacks between erosion and fracture formation and propagation, reviewed in the text, organized by spatial and temporal scale. Line drawings depict the effects in a simplified manner, photographs illustrate examples, and we provide relevant informative references for each topic. Dashed lines represent fractures, while solid lines represent surfaces. Arrows indicate flow direction. References: [1] Molnar, 2004; [2] Matthes, 1930; [3] Collins and Stock, 2016; [4] Andersen *et al.*, 2015; [5] Iverson, 1991; [6] Orlando *et al.*, 2016; [7] Strahler, 1952; [8] Aich and Gross, 2008; [9] Hancock *et al.*, 1998; [10] Whipple, 2004. [Colour figure can be viewed at wileyonlinelibrary.com]

experience less restrictive water flow conditions, allowing for more susceptibility to frost-cracking under certain conditions (Figure 5c; Andersen *et al.,* 2015). This may contribute to the sustained erosion of peaks in alpine regions (Hales and Roering, 2009). Beneath glaciers, cavity water pressure fluctuations exert stress within fractures, propagating fractures to detach blocks and enable transport (Figure 5d; Iverson, 1991). This process may lead to a positive feedback whereby over-deepened sections of the bed result in crevassing at the glacier surface just upstream, leading to increased subglacial water pressure fluctuation in the over-deepened section (Hooke, 1991). However, it is important to note that in postglacial landscapes, plucked surfaces commonly follow preglacial joint sets, potentially indicating that glaciogenic joints are not important in forming pluckable blocks (Hooyer *et al.,* 2012). Water pressure at the bed exerting pressure on fracture tips, however, likely plays an important role in decreasing friction along fracture surfaces, making preglacial fractures easier to exploit via plucking.

In vegetated landscapes, chemical weathering and biota play an important role in fracture propagation. Fractures strongly influence the pattern of rock weathering and the structure of regolith by promoting deep water infiltration into rock. Positive feedbacks can occur due to water table fluctuations, whereby oxidative weathering can create small fractures that enable the further infiltration of water and subsequent oxidative weathering (Figure 5e; Orlando *et al.,* 2016). As fractures grow, more rock surface area is exposed to oxidation, enhancing fracture generation by oxidation.

Fractures also act as a beneficial habitat condition for the existence of certain plants when soil mantles are thin (Burkhardt and Tisdale, 1969; Loope, 1977; Sternberg *et al.,* 1996; Wiser *et al.,* 1996; Hubbert *et al.,* 2001; Aich and Gross, 2008). Because plant roots tend to follow fractures (Sternberg *et al.,* 1996; Hubbert *et al.,* 2001; Brantley *et al.,* 2017), they exert both physical and chemical forcings that serve to propagate fractures (Figure 5f). By shrinking and swelling due to water intake, and eventually growing within fractures, roots exert pressure along fracture walls (Strahler, 1952), probably leading to fracture propagation. By physically enlarging fractures and interacting with infiltrating water, roots create conditions favorable for chemical weathering along fracture walls, further enhancing fracture propagation and creating a positive feedback similar to that described earlier for oxidative weathering (Phillips *et al.,* 2008; Brantley *et al.,* 2017).

In rivers, two processes have been proposed for propagating fractures. Both processes depend on the presence of sediment as well as on at least partially exposed and fractured bed.

First, hydraulic clast wedging may act to enlarge fractures through the process of pushing a clast into a fracture (Figure 5g). The clast acts as a wedge, exerting high pressure on the fracture side walls, which likely results in cracking at the fracture tip (Hancock *et al.,* 1998). This process has thus far only been inferred from the observation of clasts wedged tightly in fractures on the bed and walls of bedrock rivers. It is unclear whether these clasts are bashed into fractures by larger, saltating clasts or whether hydraulic forces serve to slightly widen fractures during high magnitude floods, allowing clasts to be emplaced within the fracture and trapped as the fracture closes, acting as ratchets that prevent the fracture from closing back to its original state after being widened (Hancock *et al.,* 1998).

Second, coarse, saltating particles impart high pressures on channel beds when they impact the bed, likely causing macroabrasion, or the formation and propagation of fractures in the bedrock (Figure 5h; Chatanantavet and Parker, 2009; Whipple, 2004). The stress imparted by particles impacting the bed can serve to both form impact fractures, which can create small blocks able to be plucked from the bed, and exert stress on blocks bound by pre-existing fractures, potentially detaching those blocks and allowing entrainment.

Synthesizing Current Understanding of Fracture Influences on Landforms and Landscapes to Identify Future Directions

Fractures have been investigated at all scales in all relevant geomorphic process domains strongly influenced by the presence of bedrock. Here, we bring together these investigations to present a group of related ideas and knowledge gaps to make it easier to use lessons learned from diverse process domains and scales to inform future investigation. Addressing the knowledge gaps identified here will be difficult without acknowledging the similarities between fracture influences on geomorphic processes at various scales and in various domains. Table I presents a list of what we find to be the most pressing questions and knowledge gaps related to fracture influences on geomorphic processes.

In terms of research in specific process domains, our literature review broadly reveals a bias towards glacial, fluvial, and hillslope domains. While there has been some research into fracture influences on coastal geomorphology (see earlier), both the coastal and aeolian domains remain ripe for basic research into this topic.

Process dominance in eroding bedrock

The dominance of plucking versus abrasion in glacial and fluvial domains is likely strongly related to fracture geometry (Whipple *et al.,* 2000a; Anderson, 2014). More widely spaced fractures produce larger blocks that generally require more stress to entrain and transport, although the relationship between block entrainment and block size is complex (Dubinski and Wohl, 2013; Lamb *et al.,* 2015). If blocks are too big for the flow to entrain and transport, plucking may yield in dominance to abrasion, whereby the blocks are eroded gradually through time. In this case, however, it is still possible that surface fracture generation (macroabrasion in rivers, bed stress and water pressure fluctuation beneath glaciers) can break down large blocks to the point at which they can be plucked faster than abraded. Holding fracture density constant, orientation also likely plays a strong role in determining whether blocks can be plucked at a rate faster than the bed can be abraded. A system with only one or two fracture sets will likely produce larger blocks than one with three or more fracture sets. Similarly, the aspect ratio of blocks strongly influences the entrainment mechanism for those blocks (Lamb *et al.,* 2015), and the predicted shear stress needed to entrain the blocks. A good field example of this comes from the Christopher Creek drainage (Wohl, 2000), where reaches with upstream-dipping beds tend to exhibit higher gradients, implying higher resistance to erosion, than reaches with downstream-dipping beds. This could imply that systems dominated by vertical entrainment and pivoting about an upstream-facing step or sliding (downstream-dipping reaches) are more erodible than those dominated by sliding or toppling (upstream-dipping reaches). Other than fracture geometry, wall friction (Dubinski and Wohl, 2013; Lamb *et al.,* 2015), tensile strength (Sklar and Dietrich, 2001; Bursztyn *et al.,* 2015), and sediment supply and caliber (Sklar and Dietrich, 2004) all likely play a role in determining whether abrasion versus plucking dominates in a given system.

Table I. A list of prominent questions that present future opportunities for developing our understanding of fracture impacts on geomorphic processes, organized by general topic

Topic	Questions
Process dominance in eroding bedrock	
	• Under what conditions does plucking dominate over abrasion in glacial and fluvial erosion?
	• Can we infer process dominance from channel form (i.e. sculpted versus blocky forms)?
	• Which fractures (of what orientation relative to flow or gravity) matter most in determining the erodibility of a pluckable block?
	• In the case of downstream-dipping beds, when does sliding entrainment dominate over vertical entrainment and pivoting about an upstream-facing step?
	• What is the mechanism by which fractures influence channel planform, and do fractures influence planform in both abrasion and plucking dominated channels?
Identifying relevant scales for understanding fracture influences on geomorphic processes	
	• For a given process, at what scales is fracture geometry relevant, and at what scale should it be measured?
	• Under what conditions do surficially generated fractures versus pre-existing, deep fractures dominate in influencing erosion rates and styles?
	• At what spatial scales and magnitudes of erosive stress do fractures dominate over flow dynamics in determining the shape and orientation of landforms and bedforms?
Understanding fracture geometry influences on erosion rates	
	• Can erodibility be described by fracture geometry alone, or are variables that are more difficult to measure necessary (e.g. fracture continuity, aperture, roughness)?
	• What is the nature of the relationship between fracture characteristics and erodibility across process domains?
	• How does fracture geometry influence the mechanism by which blocks are plucked by a flow (i.e. under what geometries do various mechanisms dominate), and does plucking mechanism regulate erosion rate?
	• How do fractures affect erosion rates due to abrasion in rivers and glaciers?
	• How is knickpoint migration affected by fracture geometry?
	• How can we translate work on idealized, cuboid fracture systems to natural systems with varying fracture geometry?
Understanding feedbacks on fracture propagation	
	• Under what conditions do topographically induced stress fractures act as a positive versus negative feedback on incision?
	• Does hydraulic clast wedging play a role in fracture propagation, how widespread is this process, and how does it function?
	• Does vegetation become more effective at propagating fractures when fractures grow larger (i.e. when roots within fractures grow), which may imply a positive feedback?

Glacial systems seem to share many characteristics with fluvial systems in terms of the dominance of plucking versus abrasion. There appears to be a threshold fracture spacing (scaled to the erosive power of the flow) that determines whether plucking is possible. In both systems, there are mechanisms for generating fractures in bedrock to enable plucking (macroabrasion in fluvial systems, subglacial water pressure fluctuations or ice-sliding driven shear stress in glacial systems), but the contribution of such autogenic fracturing to erosion rate, especially in systems with pre-existing fractures, is poorly understood. Finally, fracture orientation appears to play a role in determining the dominance of plucking versus abrasion and erosion rate in both fluvial (where it can affect plucking entrainment mechanisms, Wende, 1999; Lamb *et al.,* 2015) and glacial (where it can affect the surface area exposed to plucking versus abrasion, Kelly *et al.,* 2014; Lane *et al.,* 2015) systems. The progress made in each domain varies, but given these similarities, we suggest that future investigations into process dominance consider results from both domains, as it is likely that such a synthetic approach could result in more well-informed ideas to better understand the impact of fracture geometry on process dominance.

The potential dominance of plucking versus abrasion and the aforementioned ideas are summarized conceptually in Figure 6 by considering both the scale of erosivity (via dimensionless shear stress, or some other metric representative of erosive power) and the scale and nature of fracturing (e.g. many fractures along a single channel reach versus a few sparsely distributed fractures across a landscape). As Figure 6 implies, the relationship between dimensionless shear stress and process dominance is likely non-linear, as there are probably a set of thresholds (in block size, fracture orientation, wall friction, etc.) that define the transition from abrasion to plucking. This conceptualization greatly simplifies the characteristics that likely play a role in determining process dominance. We emphasize that a model for predicting whether abrasion or plucking will dominate in a given system has yet to be developed. Such a model should integrate understanding from glacial and fluvial erosion and ideally apply to both domains, as similar ideas have arisen in both domains (e.g. that fracture orientation and spacing relative to the direction and magnitude of flow strongly influence how easily blocks may be plucked). A better prediction of process dominance is essential for accurately parameterizing landscape evolution models that seek to produce realistic predictions while acknowledging pre-existing or high-flow generated discontinuities in rock. We suggest the conceptualization of Figure 6 as being useful to contextualize and draw similarities between investigations at varying scales and in varying domains.

Identifying relevant scales for understanding fracture influences on geomorphic processes

The question of whether abrasion dominates over plucking is fundamentally a question of scale. At small temporal scales, abrasion can easily dominate, as plucking can be infrequent. However, over long temporal scales, stress will likely exceed the plucking threshold or that threshold stress may be sufficiently decreased by surface fracturing producing smaller blocks, engendering potentially rare but effective plucking episodes (Figure 6). It is also possible that the duration between plucking events is long enough that abrasion does more work over the course of long time-periods. It is important for landscape and morphodynamic modeling to identify the temporal thresholds that separate process dominance to ensure that models accurately parameterize the importance of abrasion versus plucking.

With regard to spatial scale, the abundance and depth of surface fractures may be the dominant fracture geometry

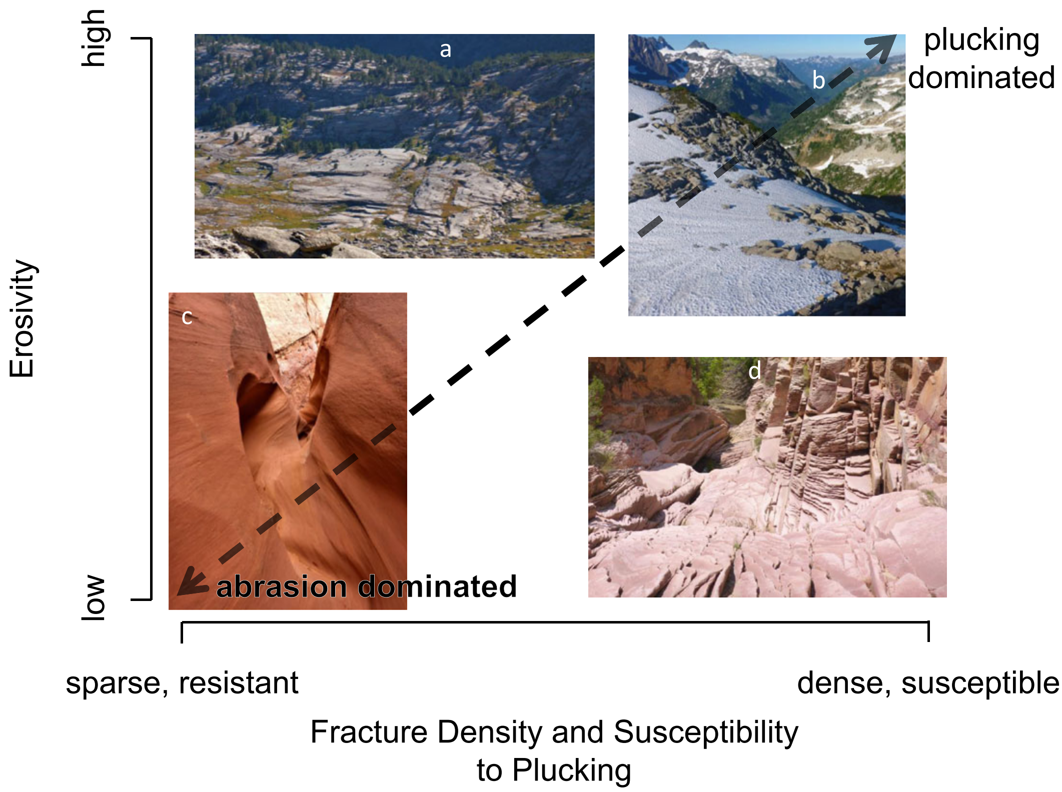

Figure 6. Conceptual, hypothesized diagram of the factors influencing the dominance of plucking versus abrasion in a fluvial or glacial system. This diagram assumes that abrasion can be dominant over the timescale of interest. The ordinate describes the erosivity of the process shaping the landscape (quantifiable by, for example, dimensionless shear stress). The abscissa describes both fracture density (sparse fractures being widely spaced and dense fractures being closely spaced) and the susceptibility of fractures to plucking due to their orientation relative to flow. Resistant might describe tetrahedral blocks with faces oriented mainly parallel to flow that experience low drag, while susceptible may describe cuboid blocks on a knickpoint lip, prone to sliding or toppling. Although fracture density and susceptibility (orientation) are represented on the same axis here for simplicity, we do not mean to imply that the two are correlated. Plucking dominates whenever erosivity is high enough to erode blocks of a given size (represented by fracture density) and orientation (represented by susceptibility). Pictures show field examples that we hypothesize to fit in various parts of the diagram. Pictures show: (a) a glacially plucked and abraded valley bottom with low fracture density that was still dominated by plucking below Dog Tooth Peak, Wind River Range, WY; (b) a densely jointed and dominantly glacially plucked surface with a small modern glacier on the east flank of Mount Hinman, WA; (c) an undulating, sculpted reach with no evident fractures in No Kidding Canyon (a tributary of North Wash), UT; (d) a densely jointed and dominantly plucked reach of Outlaw Canyon (a tributary of the Yampa River in Dinosaur National Monument), CO. [Colour figure can be viewed at wileyonlinelibrary.com]

parameter controlling a process (e.g. Chatanantavet and Parker, 2011), whereas the location or spacing of only the deepest or most persistent fractures may best relate to other processes (e.g. Hooyer *et al.*, 2012; Ortega-Becerril *et al.*, 2016). We currently lack an understanding of which fracture characteristics are relevant for a given spatial scale to best predict the erosion rate of a given process.

There remains an open question as to the importance of various fracture sets at different spatial scales. Analytical work examining individual blocks indicates that fracture characteristics that set block height, protrusion above the bed, and length likely set entrainment thresholds and, in detachment-limited systems, erosion rates (Lamb *et al.*, 2015). Results at the valley to catchment scales, however, indicate that subvertical fractures oriented subparallel to stream planform primarily determine planform and potentially erosion rate (Pelletier *et al.*, 2009). In general, it is still unclear which fracture set orientations relative to flow direction dominantly control erosion rates. It is also unclear whether orientation controls plucking erosion to the same degree as average fracture density (which sets the mean size of blocks on the bed). Although work on hillslopes has indicated that certain orientations of fractures lead to a higher likelihood of failure (Brideau *et al.*, 2009; Loye *et al.*, 2012), similar progress has yet to be made in the glacial or fluvial domains. Fracture continuity, aperture, and wall friction also have not been thoroughly investigated in terms of their impacts on glacial and fluvial erosion.

Understanding fracture geometry influences on erosion rates

Across domains, the orientation of erosive forces relative to fracture orientations can determine how easily blocks are removed from bedrock. Many studies document how ice or water flow directions or simply the orientation of hillslopes relative to fracture orientations influence the development of bedforms and the style of erosion (e.g. Lamb and Dietrich, 2009; Naylor and Stephenson, 2010; Loye *et al.*, 2012; Lane *et al.*, 2015). However, a conceptual model of how fracture orientation impacts the erodibility of the landscape has yet to be developed. Lamb *et al.* (2015) make an important first step towards such a model by deriving phase diagrams for the fluvial entrainment of blocks under varying block aspect ratios. A complete phase diagram showing the erodibility of blocks based on all possibilities of fracture orientation and spacing anisotropy, even just for cuboid fracture systems, would likely be extremely complex. Therefore, we suggest moving in a direction of identifying key fracture geometry variables (e.g. the ratio of block height to length) and testing those variables to examine the components of fracture geometry that dominantly impact erosion rate and style.

The influence of fractures on non-plucking processes is also a major knowledge gap. Previous investigations are dominated by observational evidence that fractures can generate, anchor, or guide the development of sculpted forms and abrasion erosion. However, the relationship between fracture geometry and rates of abrasion remains an important unknown. Specifically, determining the effects of variation in fracture orientation, spacing, and intrinsic properties (continuity, aperture, wall roughness) on abrasive erosion rates would be a major step towards an integrated understanding of bedrock erosion processes.

Understanding feedbacks on fracture propagation

Topographically-induced stress fractures are probably the least well understood fracture propagation mechanism on large scales (Molnar, 2004), despite evidence suggesting that this process likely occurs (Molnar, 2004; Slim *et al.,* 2015; St Clair *et al.,* 2015). We are not yet at the stage where this feedback can be accurately parameterized in landscape evolution models, although such models likely would greatly benefit from such an advance. We must identify the conditions under which this process plays an important role in fracture generation (Anderson, 2015), the subsurface fracture orientations and spacings that result from predicted stresses, and the interaction between hillslope and valley bottom fracturing and alluviation in limiting valley incision rates.

On a more tractable note, small-scale feedbacks present exciting opportunities that could be addressed relatively rapidly and used to improve understanding of rock weathering in multiple environments. Hydraulic clast wedging remains almost entirely unstudied and there is nothing but circumstantial evidence that it even occurs (Hancock *et al.,* 1998). Basic foundational investigations into this process must be made to determine the role it plays in propagating deep and surficial fractures (similar to macroabrasion), how it compares to macroabrasion in preparing bedrock for eventual transport, and how the process functions (e.g. how it depends on sediment size distribution). Outside of channels, the impact of vegetation on breaking rock on hillsides remains an exciting frontier (Roering *et al.,* 2010; Marshall *et al.,* 2015). We lack a detailed understanding of the processes by which vegetation fractures rock, and the direction of potential feedbacks related to that process.

Prominent methodological challenges

Fracture influences on geomorphic processes are difficult to disentangle from other obviously important characteristics, such as tensile strength (e.g. Bursztyn *et al.,* 2015). Like other systems with numerous variables driving a given process, confounding variables left unaccounted for in previous research hinder our ability to progress. Dealing with confounding variables can be accomplished either by the use of more advanced statistical tools (e.g. multivariate modeling, factor analysis, classification) or by attempting to control confounding variables (e.g. finding comparable field sites, or carefully designing experimental conditions).

However, it is essential that investigations be grounded in a similar conceptual model, such that all potential driving variables can be tested or controlled for in attempting to examine the influences of fracture geometry on a given process. We suggest that these conceptual models be developed to integrate knowledge from all process domains and scales to encourage interdisciplinary use of previous work and make efficient progress moving forward. Integrating broader ideas, such as connectivity (e.g. Sklar *et al.,* 2017), shows promise in enabling multiple researchers to make progress cognizant of the complications of the system under investigation.

Identifying and measuring the most relevant fracture sets or types of fractures for a given process is a major challenge in relating field measurements to erosivity and erosion rates. Sedimentary bedding or metamorphic foliation, under varying circumstances, can either exert only a small effect on cohesive strength anisotropy, or can act as the dominant failure plane allowing fracturing and block removal (Saroglou and Tsiambaos, 2008). This causes confusion when measuring fracture density, especially in foliated or sedimentary rocks. If field measurement of fracture density is to be used in a predictive manner, such as for the evaluation of spillway erosion or channel evolution in response to flooding, it is imperative that the most influential fracture sets are identified and measured, as there may be some cases when measuring every discontinuity or ignoring small discontinuities like foliation may improperly represent the actual rock strength. For instance, a plucking dominated channel may primarily exploit only widely spaced and continuous fractures, while closely spaced, discontinuous macroabrasion fractures may be widespread across a channel. Measuring every macroabrasion-induced fracture may yield a much higher estimate of the spacing of pluckable fractures than is appropriate if considering plucking erosion rates. In addition, some fractures may not be obvious to the naked eye while still exerting a strong control on morphologic evolution (e.g. Ortega-Becerril *et al.,* 2016), causing obvious challenges during field measurement.

Conclusions

The configuration and rate of change of landscapes fundamentally depend on the weathering and erosion of bedrock. An extensive literature indicates that physical discontinuities in the form of fractures within the rock strongly influence bedrock weathering and erosion. Multiple processes can initiate fractures and many of these processes involve positive feedbacks with fracture propagation. Regardless of the spatial and temporal scales considered, fractures clearly influence erosion rate and style; the shape, location, and orientation of landforms; and feedbacks between erosion, fracture propagation, and the spatial distribution of rock erodibility. Across hillslope, glacial, coastal, and fluvial domains, the spacing of fractures correlates strongly with erodibility. Similarly, the combined spacing and orientation of certain fractures sets threshold stresses for the removal of blocks. In doing so, fracture geometry can set the erodibility and eventual form of the landscape, from steep hillsides to glacially scoured valleys. Insights gained from the glacial, hillslope, and fluvial domains are similar in terms of the nature of the relationships between fracture geometry and erosion, implying that knowledge can be applied across scales and process domains.

Important gaps in understanding include: determining how fracture geometry influences the conditions under which specific erosional processes dominate; identifying the spatial scale at which fractures should be measured to best characterize erosion rates of specific processes; characterizing feedbacks between erosive processes and fracture propagation; developing methods to effectively incorporate confounding variables such as climatic variability and the strength of intact rock when examining fracture influences on geomorphic processes; and developing a widely applicable protocol for measuring relevant fracture geometry. This synthesis provides a conceptual framework for further investigation of fracture influences on geomorphic process across landscapes by working to identify relationships across domains and scales.

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