Preexisting fractures and the formation of an iconic American landscape: Tuolumne Meadows, Yosemite National Park, USA

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ABSTRACT

Tuolumne Meadows, in Yosemite National Park (USA), is a large sub-alpine meadow in the Sierra Nevada Mountains. Immediately adjacent to Tuolumne Meadows—and underlain by the same bedrock lithology (Cathedral Peak Granodiorite)—are vertical rock faces that provide exceptional opportunities to climbers. While the presence of a broad meadow suggests bedrock erodibility, the vertical rock walls indicate bedrock durability. We propose that the Tuolumne Meadows's landscape is the result of variable glacial erosion due to the presence or absence of preexisting bedrock fractures. The meadows and valleys formed because of concentrated tabular fracture clusters—a distinctive and locally pervasive type of fracturing—that were particularly susceptible to glacial erosion. In contrast, the vertical rock walls consist of sparsely fractured bedrock that was originally bounded by zones of pervasive tabular fracture clusters. Glacial erosion preferentially removed the highly fractured rock, forming prominent ridges in the upland surrounding Tuolumne Meadows. The orientation and spacing of the tabular fracture clusters, relative to ice flow, has exerted a fundamental control on the geomorphology of the area. The erosional variability exhibited by a single lithology indicates that the degree of fracturing can be more important than the host lithology in controlling landscape evolution.

INTRODUCTION

Tuolumne Meadows in Yosemite National Park is an iconic American landscape: It is a sub-alpine meadow surrounded by glacially sculpted granitic outcrops in the Sierra Nevada Mountains. Owing to its accessibility and aesthetic appeal, it has been a focal point for both vacationers (up to ~4,200 people per day according to a 2014 National Park Service report [p. ES-19]) and geological research in the Sierra Nevada (e.g., Coleman and Glazner, 1997; Loheide et al., 2009; Lowry et al., 2011). It also has historical significance; the idea for a Yosemite National Park came to John Muir and Robert Underwood Johnson over a campfire there (Duncan, 2009, p. 52).

As the largest sub-alpine meadow in the Sierra Nevada (Matthes, 1930, p. 15), Tuolumne Meadows is also a geomorphic anomaly (Fig. 1). The presence of broad and open topography is commonly associated with bedrock erodibility (e.g., Augustinus, 1995; Glasser and Ghiglione, 2009; Krabbendam and Glasser, 2011). In contrast, the nearby vertical rock walls—including Cathedral Peak, Matthes Crest, and Lembert Dome—suggest bedrock durability. Despite these geomorphic differences, the entire region is underlain by the same lithology, the Cathedral Peak Granodiorite (Bateman, 1992).

In this paper, we present evidence that this anomalous landscape is the result of preferential glacial erosion of highly fractured bedrock. In particular, tabular fracture clusters (TFCs) are common in the Cathedral Peak Granodiorite in the Tuolumne Meadows area (Riley and Tikoff, 2010; Riley et al., 2011). TFCs are dense networks of sub-parallel opening-mode fractures that are clustered into discrete, tabular (book-like) zones. We conclude that Tuolumne Meadows resulted from ice flowing perpendicularly to high TFC concentrations. In contrast, ice flowing parallel to variable TFC concentrations formed the vertical rock walls. Thus, the exceptional rock climbing around Tuolumne Meadows is a direct result of fracture-controlled variations in erodibility—on the 10–100 m scale—within a single lithology. This finding supports the contention that landscape evolution is strongly controlled by bedrock fracturing (e.g., Matthes, 1930) and that tectonic processes that result in fracturing may generally exert a fundamental and underappreciated role in geomorphology (Molnar et al., 2007).

PREVIOUS WORK ON PREEXISTING FRACTURES AND GEOMORPHOLOGY IN YOSEMITE NATIONAL PARK

Yosemite National Park is justifiably known as the landscape of John Muir. Yet, it is equally the landscape of François Matthes, despite the fact that he is much less well known, even among geologists. Matthes studied Yosemite's geomorphology for 25 years (Schaffer, 1997, p. 63–70) before publishing a benchmark paper (Matthes, 1930) in which he concluded that fracture concentrations were responsible for the size, shape, and location of the roches moutonnées as well as for the morphology of its stair-stepped valleys (see figures 33 and 34 *in* Matthes, 1930). He also observed that stair-stepped valleys formed where fracture concentrations were oriented transverse to ice flow and speculated that deep, straight, and flat-floored valleys, such as Tenaya Canyon, formed where fracture concentrations were parallel to ice flow. Matthes (1930, p. 91) concluded that variability in fracture concentration and orientation was "the key to the secret of the Yosemite's origins."

Over the subsequent 84 years, there have been significant advances in our understanding of fracture development (e.g., Lockwood and Moore, 1979; Martel, 2006) and the geomorphology

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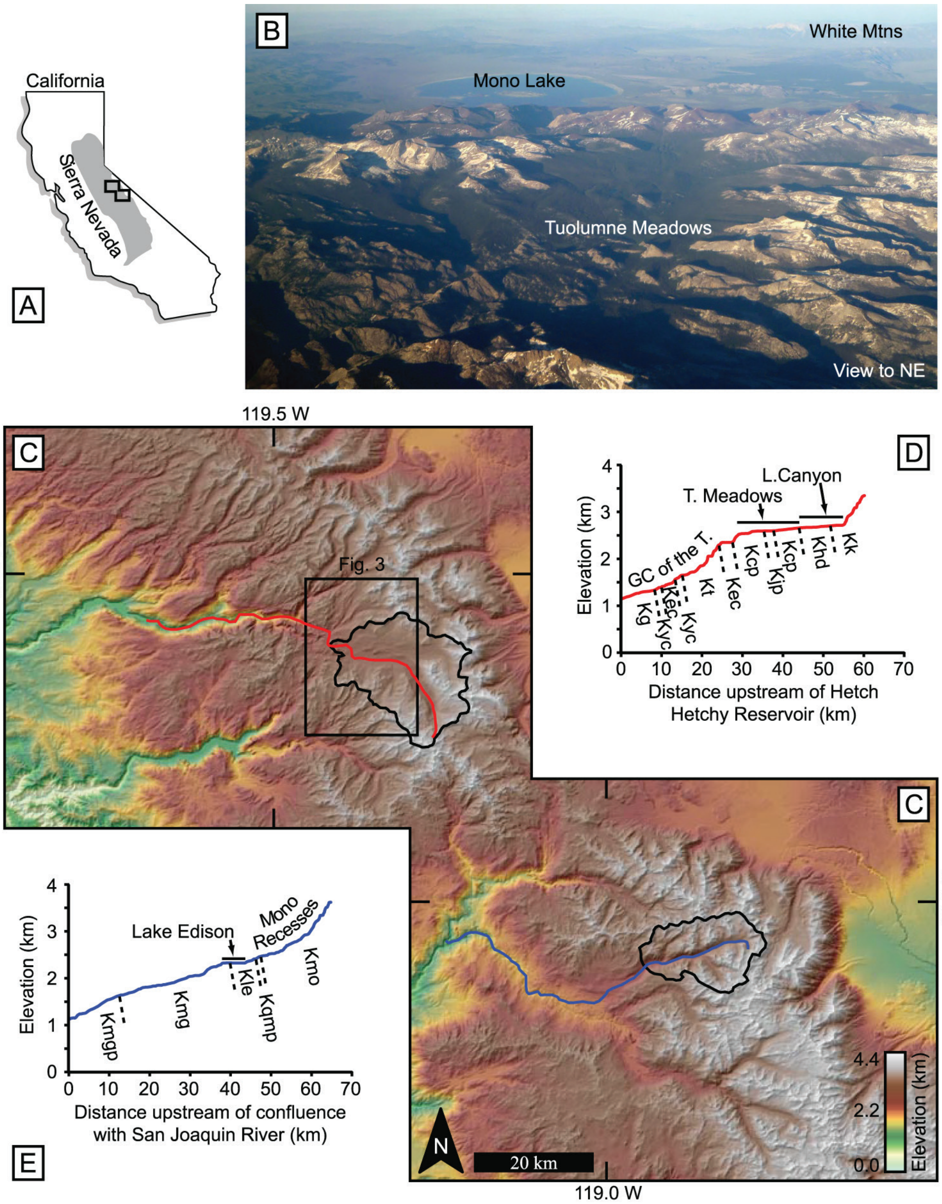

Figure 1. (A) Outline of California and the Sierra Nevada Mountains, showing panel C's position. (B) Tuolumne Meadows from the southwest; courtesy of Heidi Crosby. (C) Shaded digital elevation model, colored by elevation, of the central Sierra Nevada. Red and blue lines are the traces of the stream profiles described below in D and E. The drainage basins of the Tuolumne River above Little Devils Postpile (i.e., the Tuolumne Meadows area) and of Mono Creek above Lake Edison (i.e., the Mono Recesses) are shown. The black box indicates Figure 3's location. (D) Longitudinal profile of the Tuolumne River above Hetch Hetchy Reservoir. The locations of Tuolumne Meadows, the Grand Canyon of the Tuolumne, and Lyell Canyon are indicated. Topography from USGS maps; geology from Huber et al. (1989). Lithologic abbreviations: Kg—Undivided Cretaceous(?) granitic rocks; Kyc—Yosemite Creek Granodiorite; Kec—El Capitan Granite; Kt—Taft Granite; Kcp—Cathedral Peak Granodiorite; Kjp—Johnson Granite Porphyry; Khd—Half Dome Granodiorite; Kk—Kuna Crest Granodiorite. (E) Longitudinal profile of the South Fork of the San Joaquin River above its confluence with the San Joaquin River and continuing up Mono and Golden Creeks. Topography from USGS maps; geology from Bateman et al. (1971) and Lockwood and Lydon (1975). The artificially dammed Lake Thomas Edison is noted. Lithologic abbreviations: Kmgp—Mount Givens Granodiorite, porphyritic; Kmg—Mount Givens Granodiorite, equigranular; Kle—Lake Edison Granodiorite; Kqmp—porphyritic quartz monzonite; Kmo—Mono Creek Granite (from Bateman, 1992).

of the Sierra Nevada (e.g., Stock et al., 2004). The interaction of preexisting fractures and glacial erosion rates, however, has remained difficult to address. Dühnforth et al. (2010) helped quantify the role of fracture spacing in the glacial erosion of the Tuolumne River drainage. They dated 28 glacially striated outcrops and found that six outcrops contained inherited ^{10}Be from pre-glacial exposures. These six locations averaged fracture spacings of 3.3 m, whereas other, fully reset outcrops averaged 1.1 m between fractures. Dühnforth et al. (2010) concluded that the spacing of preexisting fractures exerts an important influence on the rate and style of glacial erosion and emphasized the efficiency of quarrying (in contrast to abrasion).

TABULAR FRACTURE CLUSTERS: A MESOZOIC INHERITANCE OF WEAKNESS

Assessing the geomorphic significance of preexisting fractures around Tuolumne Meadows requires recognition of a distinctive and locally pervasive fracturing style that is particularly erodible. TFCs were first described based on Cathedral Peak Granodiorite outcrops in the Tuolumne Meadows area (Riley and Tikoff, 2010). TFCs in this locality are bands of closely spaced (<1 cm), opening-mode fractures that occur in zones 4–40 cm wide and 3–100 m long (Fig. 2).

Opening-mode fractures, such as joints, typically do not exhibit clustered distributions. Rather, opening-mode fractures are generally anti-clustered and display a fairly regular spacing in a given locality and lithology due to the stress shadow that forms as a result of joint propagation (e.g., Price, 1966; Hobbs, 1967; Gross, 1993). So, how did the TFCs form? The map pattern of TFCs in the Tuolumne Meadows area (Fig. 3) provides information about their origin. TFCs only occur in the ca. 88.1 Ma Cathedral Peak Granodiorite—but adjacent to the mapped and geophysically inferred extent (Titus et al., 2005) of the ca. 85.4 Ma Johnson Granite Porphyry (U-Pb dates on zircon from Coleman et al., 2004). This distribution, and the clustered nature of TFCs, led Riley and Tikoff (2010) to conclude that they formed by dynamic

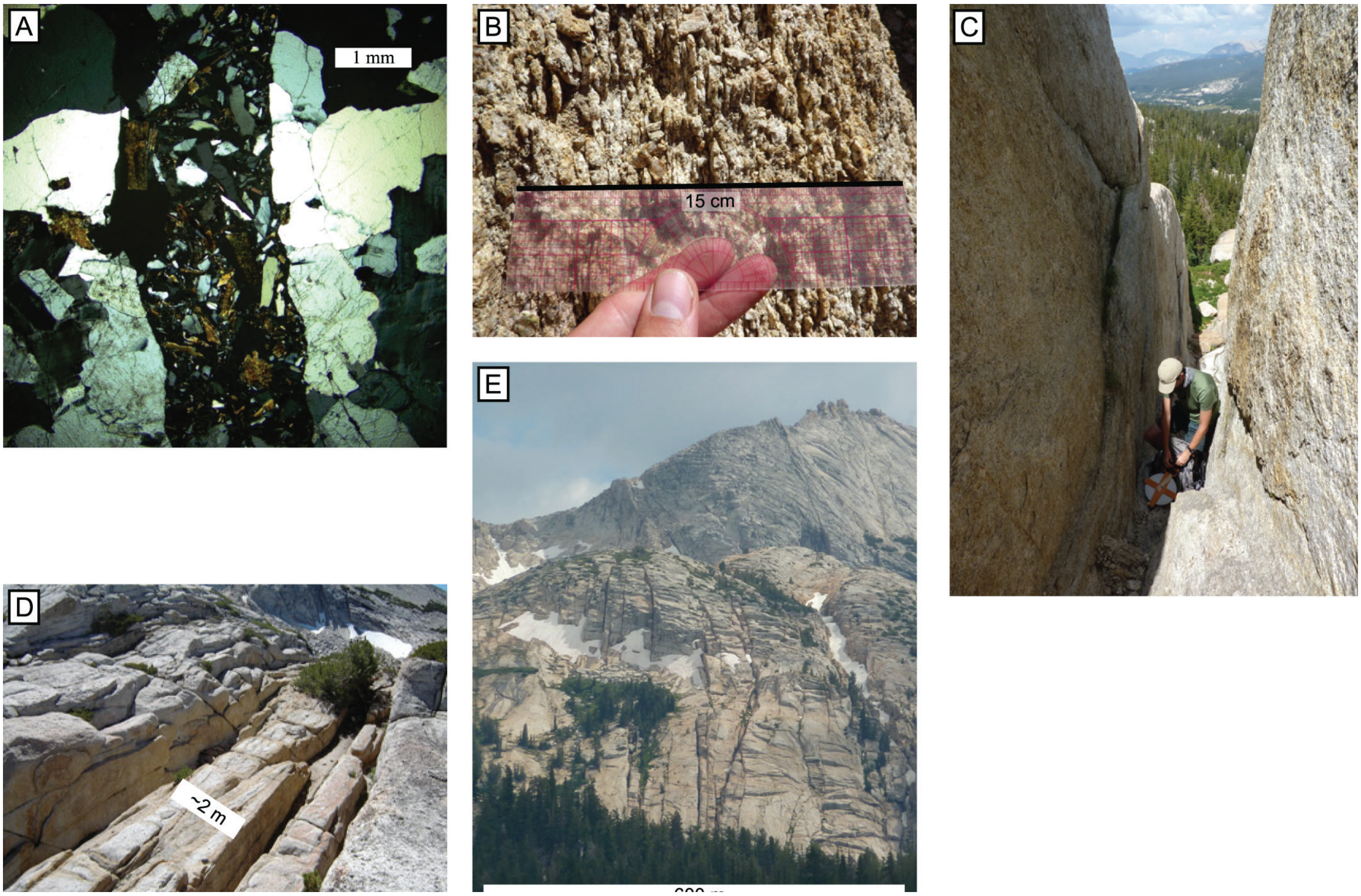

Figure 2. (A) A cross-polarized photomicrograph of an individual fracture from a tabular fracture cluster (TFC). Angular clasts are found within the fracture, and the matching grains on either side indicate a lack of shearing. (B) Photograph of a TFC illustrating their highly fractured nature, with abundant vertically oriented fractures separating thin (<1 cm) panels of unfractured rock. (C) Bedrock furrow that was eroded by ice flowing parallel to the TFC exposed along the furrow's bottom. (D) The outcrop-scale geomorphic expression of TFCs oriented parallel to ice flow; at least one TFC is located along the bottom of every bedrock furrow. (E) Furrows in the bedrock slope between Budd Lake and Tuolumne Meadows, resulting from the preferential erosion of TFCs oriented parallel to ice flow.

fracturing associated with fluid release from the crystallizing Johnson Granite Porphyry. This interpretation is further supported by microbreccia observed within the individual fractures of TFCs (Fig. 2A). The association of TFCs with magmatic structures in the Tuolumne Intrusive Suite clearly indicates that they are Cretaceous, similar to other fractures in the Sierra Nevada (Segall et al., 1990).

TFCs likely underlie all of Tuolumne Meadows, although it is not possible to directly observe the bedrock below the Meadows because it is obscured by Quaternary sediments. There are, however, three indications that TFCs are locally abundant. First, TFCs are concentrated in the bedrock slopes north and south of Tuolumne Meadows and strike into the valley from both sides (Fig. 3). Second, although there are only a few small bedrock outcrops in the Meadows proper, TFCs are common there. In fact, TFCs occur in two orientations: a dominant NNE-SSW orientation and a subsidiary, approximately orthogonal WNW-ESE orientation. Because these TFC-laden outcrops in Tuolumne Meadows are surrounded by sediment, we infer that they were less erodible—and less fractured—than the concealed bedrock beneath Tuolumne Meadows. Third, a gravity survey determined that the Johnson Granite Porphyry is within 500 m of the surface in Tuolumne Meadows (Titus et al., 2005). Because TFCs are attributed to dynamic fracturing caused by fluid release from the Johnson Granite Porphyry into the surrounding Cathedral Peak Granodiorite (Riley and Tikoff, 2010), the bedrock of Tuolumne Meadows likely hosts a high TFC concentration.

The significance of TFCs for landscape development is that they are zones of profound erodibility. The clustered nature of the fractures *within* a TFC makes any individual TFC susceptible to preferential erosion (Fig. 2C). However, the TFC zones themselves are also clumped, ranging from the outcrop (10–100 m) to map (kilometer) scales (Fig. 3). Areas where TFCs are closely spaced are highly erodible (Fig. 2D). Zones of unfractured bedrock, surrounded by individual or "clumps" of TFCs, occur as prominent and often linear topographic highs (e.g., Matthes Crest).

BEDROCK TWINS, GEOMORPHIC COUSINS

We hypothesize that high TFC concentrations allowed the formation of Tuolumne Meadows's broad and open topography. To test this hypothesis, it would be ideal to know what the landscape would look like without TFCs. The bedrock geology of the Sierra Nevada provides this analog: Tuolumne Meadows can be directly compared with the landscape of the Mono Recesses. The

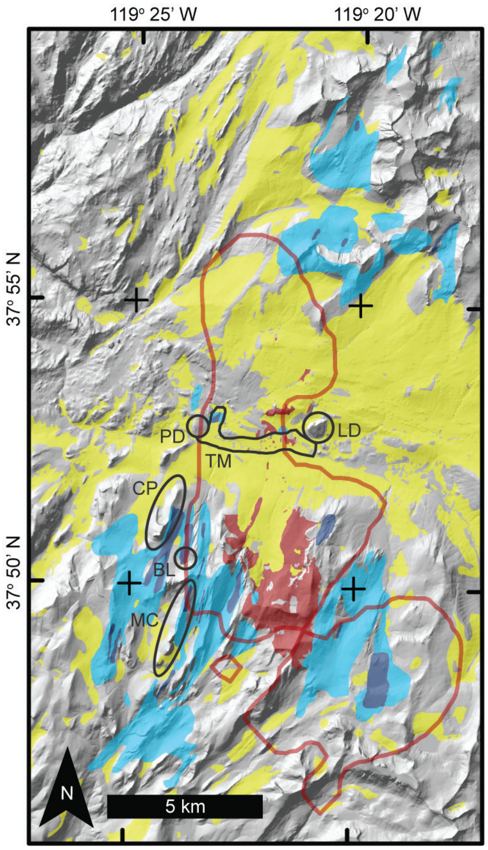

Figure 3. Geologic map draped on Tuolumne Meadows's topography (see Fig. 1 for location). Red regions represent Johnson Granite Porphyry outcrops. The rest of the map area is mostly Cathedral Peak Granodiorite. The red line represents the inferred subsurface extent of the Johnson Granite Porphyry (after Titus et al., 2005), which correlates well with the distribution of tabular fracture clusters (TFCs; blue). Light blue indicates low TFC density (2–5 m spacing) and dark blue indicates high TFC density (<2 m spacing) (after Riley and Tikoff, 2010). Yellow signifies Quaternary sediment cover. Tuolumne Meadows proper (TM) is indicated, as are Budd Lake (BL), Cathedral Peak (CP), Lembert Dome (LD), Matthes Crest (MC), and Pothole Dome (PD). Tuolumne Meadows is inferred to overlay highly fractured bedrock that was preferentially eroded by glaciation (see text for details).

Mono Recesses are located within Mono Creek's drainage basin above Lake Thomas Edison, ~70 km southeast of Tuolumne Meadows. The bedrock geology there is an en echelon series of Cretaceous plutons (the John Muir Intrusive Suite; Bateman, 1992) that are identical in age and composition with the Tuolumne Intrusive Suite, hence the phrase, "Twin of the Tuolumne" (Gaschnig et al., 2006). In particular, the Cathedral Peak Granodiorite (Kcp on Fig. 1D) is nearly identical in composition to the Mono Creek Granite (Kmo; Fig. 1E). The geological histories of the drainage basins are similar, and both are located along the Sierra Nevada's western crest. The major differences are that the Mono Recesses have few to no TFCs and the topography there is that of classic, glacial U-shaped valleys (Fig. 1C).

A comparison of the topography reveals that the landscapes are similar (e.g., glacially eroded) but not identical (Fig. 1C). The Tuolumne Meadows area is anomalously broad for its elevation and it is surrounded by a distinct NNE-SSW topographic grain that parallels the orientation of the TFCs and other fractures (Ericson et al., 2005; Riley and Tikoff, 2010). The Mono Creek drainage is different: The drainage pattern there is basically dendritic but elongated parallel to the Sierra Nevada's regional slope (e.g., Matthes, 1930; McPhillips and Brandon, 2010). Thus, it suggests that the Mono Creek Granite is near isotropic in its erodibility.

The longitudinal profiles of the streams draining these landscapes also differ substantially (Figs. 1D and 1E). Readily apparent in the Tuolumne River's profile above Hetch Hetchy Reservoir is a prominent knickpoint that separates the Grand Canyon of the Tuolumne from Tuolumne Meadows (Fig. 1D). This knickpoint is unlikely to be a transient response to a fall in the river's base level because no corresponding knickpoint is observed in the South Fork of the San Joaquin River–Mono Creek profile (Fig. 1E). Likewise, it does not correspond to the confluence of another major stream with the Tuolumne River. Thus, the knickpoint is not likely associated with a step-change in ice discharge (e.g., MacGregor et al., 2000). Consequently, we infer that the bedrock of Tuolumne Meadows is more erodible than the knickpoint's bedrock. *Yet*, both locations are underlain by Cathedral Peak Granodiorite (Fig. 1D). The fundamental difference is *not* lithology, but rather TFC abundance. TFCs are rare to absent near the knickpoint but are concentrated adjacent to the Johnson Granite Porphyry (Kjp; Fig. 3) in the middle of Tuolumne Meadows. Thus, the TFCs control its broad, level expanse.

HOW TFC DISTRIBUTION CONTROLS GLACIAL EROSION

If the Tuolumne Meadows area is more erodible, by what mechanism was it eroded? The primary processes of glacial erosion are abrasion and quarrying/plucking (e.g., Iverson, 1995). Quarrying is generally thought to be volumetrically more important (e.g., Jahns, 1943; Riihimaki et al., 2005; Dühnforth et al., 2010). Gordon (1981) noted that the orientation of quarried faces was controlled by pre-glacial joint and fracture orientations, and that these faces were rarely perpendicular to ice flow. Hooyer et al. (2012) also found that ice-flow direction mattered little to quarried surface orientation, while preexisting fracture orientation was critical. In one area, a 64° change in ice-flow direction made no difference in the orientation of the quarried surfaces; the same joint set was exploited. These results suggest that preexisting fractures are as important to the quarrying process, if not more important, than the stress induced by water-pressure fluctuations in subglacial cavities.

We present an empirical framework for glacially eroded, fracture-dominated landscapes and identify three parameters linking fractures to landscape morphology: (1) TFC orientation (relative to ice flow); (2) TFC concentration; and (3) TFC "clumpiness" (the variability in spacing between adjacent TFCs). We present six scenarios in Figure 4, illustrated with examples from the Tuolumne Meadows area. Clumpiness (or clustering) can be quantified using the maximum Lyapunov exponent (Riley et al., 2011). Here, however, we adopt a qualitative measure of clumpiness as it relates to adjacent TFCs (rather than the individual fractures within them). Low clumpiness implies nearly periodic spacing, while high clumpiness indicates an irregular distribution (Fig. 4). Note that clumpiness is *not* correlated with TFC concentration; both sparsely and densely fractured areas can have identical clumpiness. We recognize that all three variables (orientation, concentration, and clumpiness) are actually continuums and that other factors (fracture aperture and

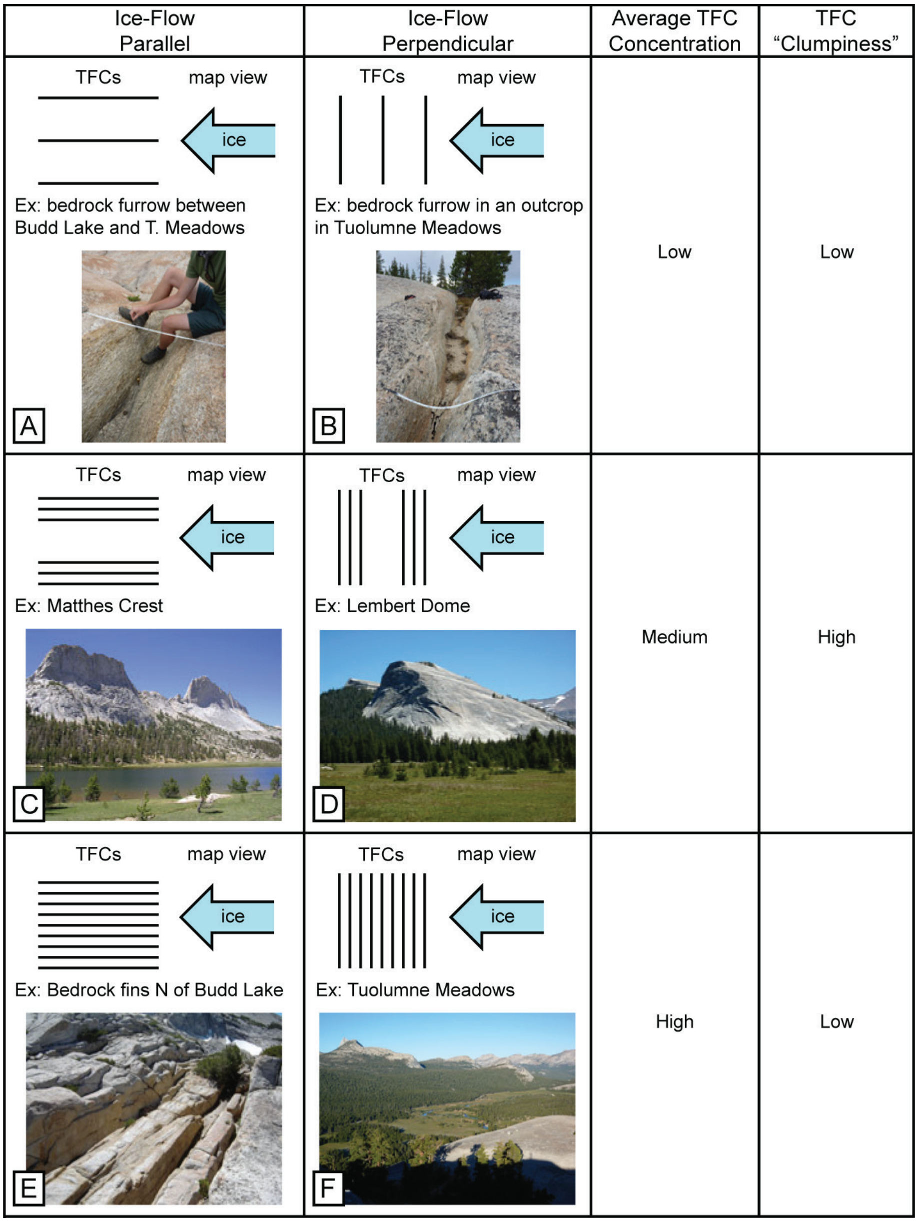

Figure 4. An empirical, conceptual framework for fracture-dominated landscapes resulting from glacial erosion, illustrated with pictures from various locations in the Tuolumne Meadows area. The effects of tabular fracture cluster (TFC) orientation (relative to ice flow), concentration, and clumpiness (or clusteredness) are considered. The best rock climbing in the Tuolumne Meadows area is associated with clumps of TFCs (middle of the diagram); here, erosion removed the more highly fractured areas, leaving the relatively *un*fractured intervening areas as ridges (if ice-flow parallel) and domes (if ice-flow perpendicular).

dip, presence or absence of multiple fracture orientations, glaciological conditions, etc.) could be incorporated if data were sufficient. In all six cases, we assume glacial quarrying was the dominant erosional process, although it deviates from the standard geometry (Fig. 5A).

Where preexisting fractures are isolated, there will be little geomorphic effect, regardless of TFC orientation (Figs. 4A and 4B). Although not well illustrated here, there may be a subtle difference in the geometry of the resulting bedrock furrows, depending on the orientation of the TFCs relative to ice flow. Some observations suggest that the furrows have a more rectangular cross section where ice flow was parallel to TFC strike. This is a qualitative impression and not always true.

The area between Budd Lake and Tuolumne Meadows (Fig. 4E) is an example of the result of ice flowing parallel to closely spaced TFCs. In this case, erosion rates are higher than those associated with isolated fractures. Since the TFCs were parallel to ice flow, the fracture zones were preferentially eroded (Figs. 2C and 2D), and a prominent series of bedrock furrows or fins resulted (Figs. 4E and 5B). An important attribute of this landscape is that the intervening, unfractured rock masses were not removed.

We propose that Tuolumne Meadows proper exemplifies a case where ice flow was perpendicular to closely spaced fractures (Figs. 4F and 5C). As discussed earlier, the bedrock volume eroded from the space now occupied by Tuolumne Meadows was

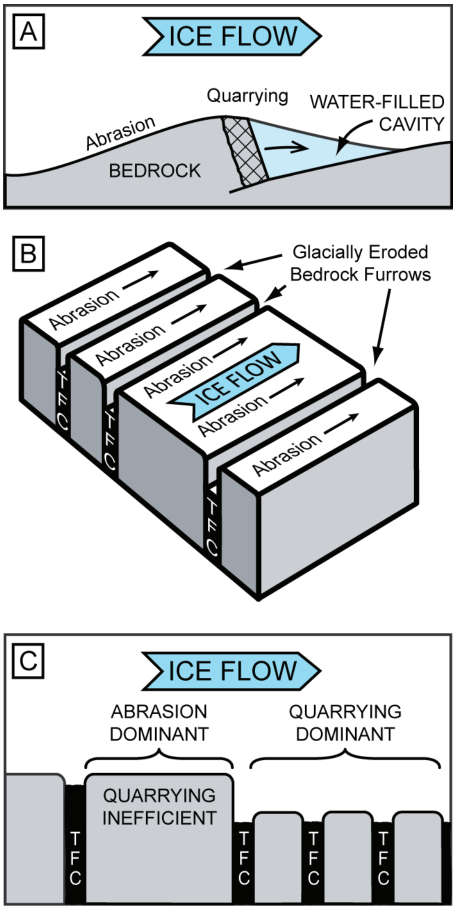

Figure 5. (A) The classic model of glacial erosion: Abrasion occurs on the stoss side of bedrock undulations, while quarrying occurs in the lee side, facilitated by water-pressure fluctuations in the subglacial cavity. (B) Glacial erosion in cases where tabular fracture clusters (TFCs) are oriented parallel to ice flow. While erosion is effective within individual TFC zones, glacial erosion is limited to abrasion on the top surface (e.g., the Budd Lake area). (C) Glacial erosion in cases where TFCs are oriented orthogonal to ice flow. Quarrying is efficient where TFCs are closely spaced (e.g., inferred for Tuolumne Meadows), but glacial erosion is restricted to abrasion where TFCs are widely spaced (e.g., up-ice section of Lembert Dome; Dühnforth et al., 2010).

likely a “chessboard” of fractured rock. Abundant fractures perpendicular to ice flow enabled the development of the anomalously flat segment in the Tuolumne River’s profile (Fig. 1D). The roches moutonnées at the east (up-ice; Lembert Dome) and west (down-ice; Pothole Dome) ends of Tuolumne Meadows are largely devoid of TFCs: Two solitary TFCs are present in Lembert Dome, and Pothole Dome only has TFCs along its eastern (up-ice) margin. The TFC concentration in Pothole Dome increases in the up-ice direction, at least until Quaternary sediments obscure the outcrop. Tuolumne Meadows is primarily oriented E-W, but here, at its westernmost extent, the valley reorients to the NNE, paralleling the dominant TFC orientation.

Thus, the case of high concentration and low clumpiness (the lower third of Fig. 4) appears ideal for quarrying. In the case of ice-flow parallel to the TFCs (e.g., near Budd Lake; Fig. 4E), glacial erosion was highly effective in the TFCs proper but did not remove the intervening, unfractured bedrock. In cases where ice flowed perpendicularly to the TFCs (e.g., Tuolumne Meadows), we infer that close TFC spacing allowed effective removal of the intervening, unfractured rock masses (Fig. 4F).

Figure 4 (middle) illustrates the high clumpiness case, in which low and high TFC concentrations alternate. The glaciation of this fracture pattern efficiently removed the fractured rock within and immediately adjacent to the TFCs. However, because of the clumped nature of the TFC distribution, large blocks of intact bedrock remained. Matthes Crest and Cathedral Peak illustrate the case of ice-flow parallel to TFCs (Figs. 4C and 5B); Lembert Dome illustrates the perpendicular case (Figs. 4D and 5C). The best climbing in the Tuolumne Meadows area is where TFC-affected bedrock has been preferentially eroded from adjoining sparsely fractured bedrock, generating vertical rock walls; in other words, where fractures are clustered.

CONCLUSIONS

Lithology is not the only—or even necessarily the most important—control on bedrock erodibility. Anderson and Anderson (2010), using data presented by Dühnforth et al. (2010), interpreted the Cathedral Peak Granodiorite as among the least erodible lithologies in Yosemite National Park. Although it can be highly resistant to erosion, we interpret the Cathedral Peak as being highly *variable* in its erodibility. In some locations (e.g., Tuolumne Meadows), it is among the *most* erodible lithologies in Yosemite. In these locations, the TFC concentration—essentially a very high fracture density—makes the rock particularly susceptible to erosion. If our hypothesis is correct, the landscape of Tuolumne Meadows illustrates that preexisting fractures influence erosion more than lithology.

This research avenue’s relevance is perhaps best described by considering the influence of tectonics on geomorphology. The primary contribution of tectonics is typically considered to be raising and lowering rock bodies relative to base level. Molnar et al. (2007), however, proposed that tectonics may instead exert its greatest influence by crushing rock masses into parcels readily transportable by surficial processes prior to their arrival at the surface. If so, our ability to characterize erodibility in terms of both lithologic and fracture characteristics is critical. TFCs are an extreme example of fracturing that may aid in characterizing the effect of more typical fracture patterns on bedrock erodibility.

We conclude that Tuolumne Meadows’s current landscape can be directly linked to a short-lived Cretaceous fracturing event associated with the Johnson Granite Porphyry’s emplacement. The orientation, concentration, and distribution (clumpiness) of the TFCs provide first-order constraints on the subsequent landscape evolution. The conceptual framework presented here—for explaining how glacial erosion proceeds in this kind of highly fractured landscape—is a result of simultaneously investigating both the bedrock geology and the geomorphology. It comes from the same tradition as F. Matthes and his 25 years of observations in Yosemite. In this respect, it is perhaps useful to remember a quote from John Muir (1911, p. 104): “When we try to pick out anything by itself, we find it hitched to everything else in the Universe.”

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