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Forum Article

Glacial and periglacial buzzsaws: fitting mechanisms to metaphors

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ABSTRACT

The buzzsaw hypothesis refers to the potential for glacial and periglacial processes to rapidly denude mountains at and above glacier Equilibrium Line Altitudes (ELAs), irrespective of uplift rates, rock type or pre-existing topography. Here the appropriateness of the buzzsaw metaphor is examined alongside questions of the links between glacial erosion and ELAs, and whether the glacial system can produce low-relief surfaces or limit summit heights. Plateau fragments in mountains on both active orogens and passive margins that have been cited as products of glacial and periglacial buzzsaw erosion instead generally represent dissected remnants of largely inherited, pre-glacial relief. Summit heights may correlate with ELAs but no causal link need be implied as summit erosion rates are low, cirque headwalls may not directly abut summits and, on passive margins, cirques are cut into pre-existing mountain topography. Any simple links between ELAs and glacial erosion break down on passive margins due to topographic forcing of ice-sheet growth, and to the km-scale vertical swaths through which ELAs have shifted through the Quaternary. Glaciers destroy rather than create low-relief rock surfaces through the innate tendency for ice flow to be faster, thicker and warmer along valleys. The glacial buzzsaw cuts down.

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Mountain glaciers, through time, create spectacular alpine relief: a rugged, all-slopes topography of sharp ridges, cookie-cut hollows, high cliffs and deep, rock-walled valleys. Glacial dissection is most intensive where mountains are rising quickly, generating some of the highest erosion rates recorded on Earth (Spotila et al., 2004). Where glacial erosion is particularly effective, the isostatic response to the loss of mountain mass contributes to further uplift (Brozović et al., 1997; Egholm et al., 2009). Efficient cold climate erosion then itself is a driver for mountain building and may limit how high or fast mountains can rise. Hence Late Cenozoic climate cooling indirectly becomes a cause of uplift when it brings highly erosive glaciers to the mountains (Molnar and England, 1990). This potential to rapidly denude topography at and above the glacier Equilibrium Line Altitude (ELA), irrespective of uplift rates, rock type or pre-existing topography, is the glacial buzzsaw hypothesis (Brozović et al., 1997; Mitchell and Montgomery, 2006).

In mountain geomorphology today, the buzzsaw has become the power tool of choice. First heard around the western Himalaya (Brozović et al., 1996), glacial buzzsaws were quickly serrating rising mountains all around the world (Montgomery et al., 2001; Brocklehurst and Whipple, 2004; Spotila et al., 2004; Mitchell and Montgomery, 2006; Pedersen et al., 2010; Sternai et al., 2011). Mountains on glaciated passive margins soon came under attack (Nielsen et al., 2009; Steer et al., 2012) and recently a new erosive accessory is heard in the hills, the periglacial buzzsaw (Hales and Roering, 2009).

Yet as buzzsaws have been deployed ever more widely across the mountains, the metaphor has become ever more distant from the tool itself. *Buzzsaw* is a North American term for a fixed, vertically-aligned, circular power saw, mainly used for cutting timber into planks (Fig. 1). Unlike actual buzzsaws, mountain buzzsaws can cut in any plane. Glacial buzzsaws are also tasked to do much more than just cut, by limiting summit heights (Mitchell and Montgomery, 2006; Egholm et al., 2009) and by grinding down or otherwise reducing low-angle surfaces (Brozović et al., 1997; Nielsen et al., 2009). Periglacial buzzsaws are regarded as equally versatile tools, cracking clasts on the wet surfaces of outwash plains (Hallet and Roche, 2010), frost shattering rock cliffs (Hales and Roering, 2005, 2009) and beveling low-angle slopes on plateaus (Nielsen et al., 2009; Goodfellow, 2012; Steer et al., 2012). In these increasingly diverse contexts, the buzzsaw metaphor often no longer retains any clear analogy with a vertical saw. The metaphor has become mixed, most strikingly in situations where the buzzsaw is required to increase relief in mountains through valley incision whilst at the same time to reduce relief by the extension of low-relief surfaces (Steer et al., 2012). Before the glacial and periglacial buzzsaws become just catch-all terms for cold climate erosion in mountains, it is timely to ask: just how do these geomorphic tools operate?

The glacial buzzsaw cuts vertically and so provides a useful mechanistic metaphor for the dissection of mountains by glaciers. Alpine glaciers can be highly effective agents of vertical erosion, forming parabolic rock channels sometimes several kilometers deep whilst flowing from cirques and into tributary and trunk valleys (Whipple et al., 1999). Beneath ice caps and ice sheets, ice flow tends to stream along pre-existing fluvial valley systems, leading to highly selective linear erosion (Sugden, 1968; Nesje and Whillans, 1994). Transfluent ice flow may lead to breaching of watersheds and to cutting of new

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Figure 1. The buzzsaw at rest. Image courtesy of Mae Nowlin.

valleys (Haynes, 1977). The most extreme manifestation of such deep glacial excavation, notably on the glaciated passive margins of Norway and Greenland, is the creation of extensive systems of fjords with their floors deep below sea level (Kessler et al., 2008).

The glacier regime powering the glacial buzzsaw is thus that of *selective linear glacial erosion* (Sugden, 1968). Valleys and valley heads in mountains act to channel ice flow. Convergence, with greater ice discharge and thickness, increases erosion along the valley axis (Hall and Glasser, 2003; Kessler et al., 2008), introducing positive feedback as the valley deepens and more ice is drawn down. On glaciated topographic highs, in contrast, ice flow is divergent and slow. Low ice-surface temperatures and low strain heating suppress basal ice temperatures, yielding cold-based and non-erosive ice covers (Kleman and Glasser, 2007). The glacial system, due to its inherent property of being warmer at low points in the terrain, is a system producing relief enhancement (Kleman, 2008) by eroding valleys deeply whilst high ridges and summits experience much slower erosion (Valla et al., 2011). Where the glacier bed is thawed and not frozen, and the flow is linearly guided, glaciers cut down and cut deep (Kleman, 2008). For those situations, the analogy with a powered circular saw is compelling.

The glacial buzzsaw, however, has been tasked since its inception to do something that the glacial system cannot efficiently do: wear back by cutting horizontally to reduce or limit relief (Brozović et al., 1997). Geophysicists working with hypsometric (area–altitude) data showed correlations, despite variable exhumation rates, between modal elevation, summit heights and ELAs in the western Himalaya (Brozović et al., 1997) and, subsequently, in other alpine mountain ranges (Mitchell and Montgomery, 2006; Egholm et al., 2009). As ice discharge and thickness for cirque and valley glaciers tend to be greatest at the ELA (Jamieson et al., 2008), glacial erosion rates are typically highest at these elevations. So the removal of rock mass at the ELA and higher elevations was attributed mainly to erosion by cirque and valley glaciers. Yet whilst glaciers can cut down effectively (Shuster et al., 2011), valleys and trough heads are widened much more slowly and then largely through the paraglacial processes involved in rock slope failure (Whipple et al., 1999; Schlunegger and Norton, 2013). Crucially, valley down-cutting leads to a sharp divergence in erosion rates, with high erosion rates on the valley floor and along its sides and much lower rates on ridges (Valla et al., 2011). This divergence is most marked and apparent when a plateau is dissected, because the low slopes on the plateau are effectively decoupled from rapid erosion (Small et al., 1997; Anderson, 2002). Glacial valleys in alpine settings can be viewed as deep slots cut by many glaciers acting as individual buzzsaws.

What then of the links between modal elevation, summit heights and ELAs in mountain ranges? In the original buzzsaw proving ground around Nanga Parbat, half of the land area lies between 4 and 5 km above sea level. The ground apparently lost to erosion at higher elevations has been attributed to extensive glacial scouring and to vigorous freeze–thaw action operating at the ELA (Brozović et al., 1997). The possibility of the survival of pre-uplift low relief was denied because of locally very high rates of exhumation (Brozović et al., 1997) but it now appears that this part of the NW Himalaya represents an uplifted portion of the Eocene Tibetan plateau (Van Der Beek et al., 2009), subsequently reshaped by differential tectonics and deep dissection by glaciers and rivers. Similar topographic inheritance is found in other alpine mountain ranges (Battiau-Queney, 1997; Palumbo et al., 2009). In part because time scales for Pleistocene glaciation are short, topographic inheritance rather than ELA-driven erosion may be the dominant control on both summit height and modal elevation in mountain ranges raised by Late Cenozoic tectonics that are not yet in topographic steady state.

The mechanisms by which accordant summit heights develop in mountain ranges have been explored for over a century (Daly, 1905) but how buzzsaw-related processes might act to limit summit heights remains unclear. Glacial and periglacial processes become less effective at the highest elevations in mountains due to rock resistance, inhibition of glacial and periglacial processes by intense cold and lack of moisture (Hallet et al., 2010) and snow- and ice-shedding "Teflon peaks" (Anderson, 2005). Rates of summit lowering are not well constrained but are probably low. Peaks may be abruptly reduced in elevation when oversteepening of flanking rock slopes by glacial erosion leads to rock slope failure (Evans et al., 2006). In alpine terrain, cirque glaciers contribute to oversteepening mainly through headward erosion but localised rock failure is unlikely to lead to widely accordant summit heights, especially as cirques seem generally incapable of removing narrow headwalls and of breaching narrow ridges (White, 1970).

Moreover, the correlation between cirque floor and summit heights found in alpine ranges need not imply that cirque erosion controls summit heights (Mitchell and Montgomery, 2006; Egholm et al., 2009). This correlation also exists on passive margin mountains (Robinson et al., 1971; Rudberg, 1994) where cirques are cut into pre-existing topography (Evans, 2006). Where cirque walls are distant from summits the retreat of cirques cannot control summit elevation.

That modal terrain elevations in mountain ranges with a large number of independent glaciers should generally coincide with ELAs is unsurprising. Topographic controls on snowline altitude (Mitchell and Montgomery, 2006) and mountain glacier location (Kessler et al., 2006) are strong. Glaciers can only erode where they exist and ELAs must lie below summit heights if glaciers are to form. The main impact of the glacial buzzsaw on mountain hypsometry and relief may be through the cutting in mountain blocks of many, closely-spaced, deep valleys and bowls with floors at concordant heights.

The inability of glacial and periglacial processes to bevel and level extensively is most obvious in passive margin settings. Uplift there is slower, and for ~2.7 Ma there have been high-frequency changes between mountain glaciers, ice sheets and periglacial environments. Conventionally, low-relief surfaces in glaciated passive margin mountains have been regarded as remnants of erosion surfaces, cut across geology and structure and formed by prolonged weathering and erosion acting under fluvial environments prior to Pleistocene glaciation (Godard, 1965; Gjessing, 1967; Lidmar-Bergström et al., 2007) (Fig. 2A). Recently, glacial and periglacial buzzsaws have been invoked to account for the existence of plateau fragments in western Norway (Nielsen et al., 2009). Leveling is attributed to elimination of drainage divides by headward retreat of cirques and valley heads, to glacial scouring and to efficient periglacial weathering (Steer et al., 2012). These cold-climate processes operated over a range of elevations as the ELA has shifted through and perhaps before the Pleistocene. Yet the plateau fragments on the uplifted Norwegian margin can be traced

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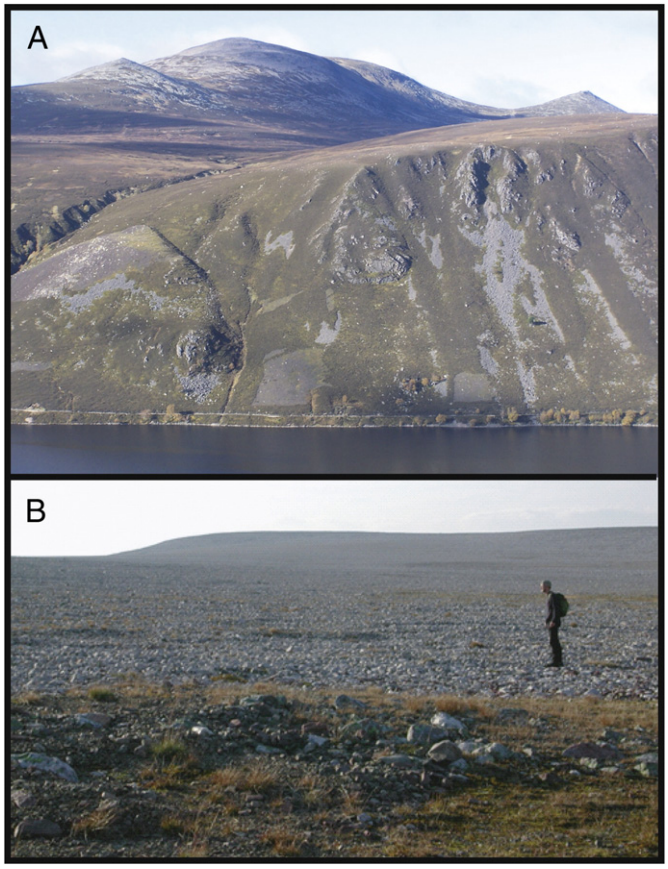


Figure 2. A. Granite domes, with summit tors, and surrounding plateau at 800 m a.s.l.) around Lochnagar, northeast Scotland. In the foreground, this old, largely inherited relief is dissected by the glacial trough of Loch Muick. B. Blockfield-covered, low-relief surface at 300–400 m a.s.l. on the Varanger Peninsula, northern Norway.

eastward into extensive low-relief surfaces in lowland western Sweden along the pre-glacial drainage lines (Bonow et al., 2003; Fjellanger and Etzelmüller, 2003; Ebert et al., 2011).The plateaus are clearly fragments of inherited, mainly pre-Pleistocene topography (Hall et al., 2013a), a widespread feature of glaciated passive margins (Briner et al., 2006; Corbett et al., 2013).

In reality, ELA-controlled erosion is not to be expected on passive margins. Plateau remnants in western Fennoscandia have experienced conditions that have varied between ice-free, ice cap, and ice-sheet glaciation under the fluctuating climates of the Pleistocene (Porter, 1989; Kleman and Stroeven, 1997). ELAs fluctuated through kilometer-scale vertical swaths. A vital component of the buzzsaw hypothesis, the connection between ELA and elevations of maximum erosion, is thus violated for most of the Pleistocene. This is because the link between ELAs and efficient glacial erosion is only valid for cirque and smaller valley glaciers, but clearly non-valid for ice sheets with their complex basal thermal zones (Kleman et al., 2008). For the area of the Fennoscandian ice sheet, efficient glacial erosion can be demonstrated for a 2.8-km vertical range, from the 1400-m deeps of Sognefjord to the demonstrably overridden and eroded cirques of the 1400-m high Sälka massif in northern Sweden (Kleman and Stroeven, 1997). ELAs have no predictive or explanatory value for such patterns.

The onset of ice-sheet glaciation and the channeling of ice flow along existing valleys led to the dissection and reduction of erosion surfaces on passive margins (Kleman and Stroeven, 1997), not to extension. Pleistocene erosion on plateau surfaces was quite modest, as shown by the widespread distribution of slowly eroding blockfields (Fjellanger et al., 2006; Corbett et al., 2013) (Fig. 2B), due to prolonged non-erosive, generally cold-based ice cover (Sugden, 1968; Phillips et al., 2006). In western Norway, the volume of Pleistocene erosion is given mainly by the rock removed from cirque basins, glacial valleys and fjords by glacial erosion (Nesje and Whillans, 1994), plus an equivalent or greater contribution from deep erosion of the coast and inner shelf (Dowdeswell et al., 2010; Hall et al., 2013a). Only on passive margins with the deepest fjords, like W Norway and E Greenland, has glacial erosion shifted sufficient rock volumes to become a significant contributor to uplift (Medvedev et al., 2008). Even here, there is a very strong coast-to-inland gradient in cirque and valley erosion so that the back-tilted parts of glaciated passive margins have experienced much lower average depths of erosion (Kleman and Stroeven, 1997; Hall et al., 2013b; Refsnider and Miller, 2013).

So is it time to power down the glacial buzzsaw? No—the buzzsaw provides an easily visualized and apt analogue for vertical glacial erosion by glaciers in mountains. This eroded mass is transported from mountains to forelands or shelves through the glacial conveyor and contributes to isostatic compensation and mountain uplift in both alpine and passive margin contexts (Montgomery, 1994; Medvedev et al., 2008; Tomkin, 2009). Yet the buzzsaw metaphor has become used indiscriminately and increasingly serves as a vague, catch-all term for efficient erosion by cold-climate processes operating in mountains. Specifically, the term *periglacial buzzsaw* often does not relate in any meaningful way to sawing or to vertical incision and should be dropped. The *glacier buzzsaw* cuts down and the term should not be applied to contexts where horizontal erosion is dominant. In terms of buzzsaw mechanisms, the glacial buzzsaw is relief-enhancing, and thereby mountain-building. Glaciers destroy rather than create low-relief rock surfaces through the innate tendency for ice flow to be faster, thicker and warmer along valleys.

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