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Testing the efficacy of the glacial buzzsaw: insights from the Sredinny Mountains, Kamchatka

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ABSTRACT

Peak altitudes, hypsometry, geology, and former equilibrium-line altitudes (ELAs) are analysed across the Sredinny Mountains (Kamchatka). Overall, evidence is found to suggest that the glacial buzzsaw has operated to shape the topography of this mountain range, but the strength of this signature is not spatially uniform. In the southern sector of the mountains, we see evidence that an efficient glacial buzzsaw has acted to impose constraints upon topography, limiting peak altitudes, and concentrating land-surface area (hypsometric maxima) close to palaeo-ELAs. By contrast, in the northern sector of the mountains, a number of peaks rise high above the surrounding topography, and land-surface area is concentrated well below palaeo-ELAs. This deviation from a classic 'buzzsaw signature', in the northern sector of the mountains, is considered to reflect volcanic construction during the Quaternary, resulting in a series of high altitude peaks, combined with the action of dynamic glaciers, acting to skew basin topography toward low altitudes, well below palaeo-ELAs. These glaciers are considered to have been particularly dynamic because of their off-shore termination, their proximity to moisture-bearing air masses from the North Pacific, and because accumulation was supplemented by snow and ice avalanching from local high altitude peaks. Overall, the data suggest that the buzzsaw remains a valid mechanism to generally explain landscape evolution in mountain regions, but its signature is significantly weakened in mountain basins that experience both volcanic construction and climatic conditions favouring dynamic glaciation.

1. Introduction

Mountain chains play an important role in governing global and regional climate patterns by acting as orographic barriers to atmospheric flow (e.g., Bookhagen and Strecker, 2008; Galewsky, 2009). Therefore investigating the processes and timescales responsible for their development is important. In general, topographic development is governed by the interaction of uplift, largely driven by tectonic processes, and denudation by various forms of weathering, erosion, and mass movement (e.g., Small and Anderson, 1995; Brocklehurst and Whipple, 2002). Across much of the globe, denudation is generally governed by fluvial and slope processes, yet in many mountainous and high to mid-latitude environments, glacial processes become dominant and represent the main players in shaping large-scale topography (see Egholm et al., 2009). The role of glaciers as denudational agents is largely governed by subglacial erosion, through a combination of abrasion, plucking, and subglacial fluvial drainage (see Krabbendam and Glasser, 2011; Cowton et al., 2012) (though associated periglacial processes also contribute). The efficacy of these mechanisms is a function of ice velocity, thickness, subglacial water pressure, and bedrock properties; but in general terms, the intensity of subglacial erosion is greatest where total ice-flux and subglacial sliding velocity are maximized (see Harbor et al., 1988; Humphrey and Raymond, 1994; MacGregor et al., 2000; Tomkin and Braun, 2002; Amundson and Iverson, 2006). For most glaciers, this area where erosion is maximized is considered to coincide with the equilibrium-line altitude (ELA) where net annual accumulation and ablation are equal (Boulton, 1996; Hallet et al., 1996; MacGregor et al., 2000; Anderson et al., 2006). The position of the ELA is governed by local factors such as topographic shading and avalanching, but at a regional scale is largely determined by climate (air temperatures and snowfall) (e.g., Ohmura et al., 1992). With glacial erosion maximized at the ELA, topography above this altitude progressively steepens, as valley sides and cirque headwalls are undercut and become prone to periglacially induced rock detachments and slope failures (Oskin and Burbank, 2005; Sanders et al., 2012). These processes act to enlarge valleys above the ELA and limit the altitudes attained by mountain peaks (Oskin and Burbank, 2005; Mitchell and Montgomery, 2006; Sanders et al., 2012). Below the ELA, erosion is limited by reduced ice flux and sliding velocity and by a system generally prone to being engulfed by glacial sediments that inhibit post-glacial fluvial erosion (e.g., Whipple et al., 1999). These combined processes of erosion and deposition above, at, and below the ELA result in the classic 'glacial

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buzzsaw' landscape, characterised by a concentration of eroded topography close to palaeo-ELAs and in a clear correlation between peak altitudes and palaeo-ELAs (Brozović et al., 1997; Montgomery et al., 2001; Brocklehurst and Whipple, 2002; Mitchell and Montgomery, 2006; Foster et al., 2008; Egholm et al., 2009; Pedersen et al., 2010). Though such a signature can be found in many mountain ranges globally (Porter, 1964; Richmond, 1965; Brozović et al., 1997), the efficacy of the buzzsaw effectively relies upon a balance between glacial and tectonic forces—and clearly, many exceptions are possible (e.g., Brocklehurst and Whipple, 2007; Foster et al., 2010; Pedersen et al., 2010; Ward et al., 2012). For example, climatic factors can enhance or inhibit the formation and erosional power of glaciers (e.g., Thomson et al., 2010), as can factors related to bedrock lithology and structure. This paper considers the role of geological and climatic forces in mitigating the glacial buzzsaw within the Sredinny Mountains, Kamchatka.

2. Previous investigations

A number of studies have considered the role of the glacial buzzsaw in regulating the topography of mountain massifs around the world. Brozović et al. (1997), investigating actively deforming mountains in the NW Himalaya, were the first to identify and outline the landscape-signature of the glacial buzzsaw. Subsequent investigations demonstrated the prevalence of this signature in the mountains of North America (Spotila et al., 2004; Mitchell and Montgomery, 2006; Foster et al., 2008, 2010; Ward et al., 2012), South America (Thomson et al., 2010), New Zealand (Brocklehurst and Whipple, 2007), Switzerland (Anders et al., 2010), and at a global scale (Egholm et al., 2009; Pedersen et al., 2010). Deviations from the 'classic' buzzsaw signature have been linked to tectonics and bedrock strength (see Foster et al., 2008, 2010; Thomson et al., 2010; Ward et al., 2012) and used to infer the former presence of minimally erosive glaciers (Thomson et al., 2010).

3. Study area

The geographical focus of this investigation is upon the Sredinny Mountains, which represent the central topographic divide of the Kamchatka Peninsula (see Fig. 1). The mountain range is ~800 km long, up to ~100 km wide, and constitutes a series of separate ridges and volcanic plateaus, with peak altitudes typically found between 1500 m above sea level (asl) and 2000 m (asl), reaching a maximum altitude of 3621 m (asl). The mountains are geologically very young and have undergone uplift and deformation during the past 70 Ma or more (Fedotov et al., 1988; Hourigan et al., 2004). The region's generalised lithology is presented in Fig. 1A (based upon Persits et al., 1997; Avdeiko et al., 2007). In total, nine units are distinguished, with ~5% of the area comprising Quaternary unconsolidated deposits; ~8% comprising Paleocene–Miocene deposits; ~32% comprising Quaternary volcanic complexes; ~30% comprising Miocene–Pliocene volcanic complexes; ~2% comprising Eocene volcanic complexes; ~3% comprising collision granitoids; ~9% comprising upper Cretaceous and Paleocene volcanic and volcanic-terrigenous deposits; ~3% comprising Cretaceous terrigenous deposits; and ~8% of the area comprising metamorphic complexes. At present, the range is occupied by 72 extinct and two active volcanoes (Avdeiko et al., 2007), some of which are characterised by considerable Quaternary activity (see Table 2).

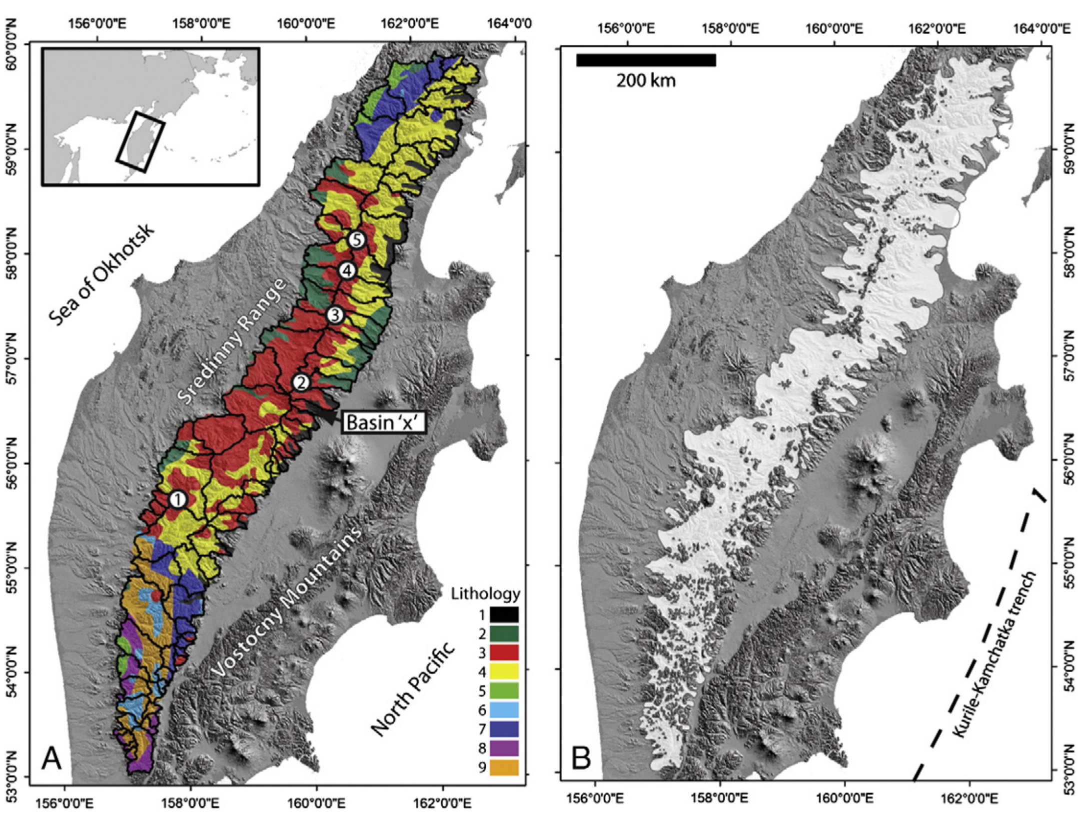

Fig. 1. Map of the Kamchatka Peninsula, focusing upon the Sredinny Mountain Range. (A) Drainage basins (N = 80) analysed in the present study (outlined in black) and generalised lithology (based upon Persits et al., 1997; Avdeiko et al., 2007). Geological units are (1) Quaternary unconsolidated deposits; (2) Paleocene–Miocene deposits; (3) Quaternary volcanic complexes; (4) Miocene–Pliocene volcanic complexes; (5) Eocene volcanic complexes; (6) collision granitoids; (7) upper Cretaceous and Paleocene volcanic and volcanic–terrigenous deposits; (8) Cretaceous terrigenous deposits; (9) Metamorphic complexes. Numbered peaks (1–5) are those extending >500 m above regional trends in peak altitude (peak details are provided in Table 2). The hypsometric attributes of basin 'x' are presented in Fig. 3. (B) The extent of glaciation in the Sredinny Mountains during the global Last Glacial Maximum (according to Barr and Clark, 2011).