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Rock glaciers and the geomorphological evolution of deglacierizing mountains

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ABSTRACT

Rock glaciers are an important geomorphic element of glaciated mountain landscapes, but our understanding of their distribution and ages, controls on their development, and their importance in regional mountain hydrology and mountain geomorphic evolution is incomplete. In part, this incomplete knowledge arises through problems associated with identifying rock glaciers on a morphological basis alone, amplified by the multiple ways in which rock glaciers can form in different glacial, periglacial, and paraglacial settings. This study focuses on rock glaciers as a paraglacial mountain landscape element and considers the relationships between rock glaciers and glacial, periglacial, and paraglacial processes. New geomorphic and sedimentary data on different rock glaciers from the Khumbu region of Nepal are presented. These data show that even within a single region, rock glaciers may have varied origins and thus likely ages and different climatic and environmental controls. We argue that rock glaciers in deglacierizing mountains may have a long residence time in the landscape, unlike many other glacially influenced mountain landforms, and can undergo significant morphodynamic changes as glaciated landscapes transition into paraglacial landscapes.

1. Introduction

Despite much recent research (e.g., Brenning, 2005; Rangecroft et al., 2015; Jones et al., 2018), the role of rock glaciers in the hydrology and morphological evolution of deglacierizing mountains remains poorly known. In part this arises from limitations of the different ways in which rock glaciers have been identified, measured, and monitored (Hamilton and Whalley, 1995; Roer and Nyenhuis, 2007; Dall'Asta et al., 2017; Deluigi et al., 2017; Kenner et al., 2018). Remote sensing-based methods are not always able to clearly resolve differences between rock glaciers, debris accumulations such as rockfalls, and glacial moraines (Kenner et al., 2014; Wang et al., 2017); and the issue of mimicry and equifinality applies, especially in the case of rock glaciers (Jarman et al., 2013). In addition, individual studies have not always used consistent methodologies, thus making it difficult to compare results between different areas. Any remote sensing methodology largely depends on the data sets used and their resolutions (spectral and temporal), and this has hindered comparability between studies. Field-based methods of quantifying rock glacier properties, their morphometry, and spatial patterns (e.g., Martin and Whalley, 1987; Humlum, 1996; Ikeda and Matsuoka, 2006) are time consuming and expensive; and many mountain regions globally have not been examined in the field by geomorphologists, although numerous inventories from individual mountain blocks have been produced (e.g., Lilleøren and Etzelmüller, 2011; Krainer and Ribis, 2012; Scotti et al., 2013; Rangecroft et al., 2014; Falaschi et al., 2015; Onaca et al., 2016). As a result, rock glaciers remain one of the most poorly understood mountain landforms (Berthling, 2011). This is particularly the case for inactive (relict) rock glaciers whose age, controls, and longevity are difficult to evaluate and whose evolution is difficult to reconstruct. Recent work has discussed the relationship of rock glaciers to paraglacial (landscape relaxation) processes following deglaciation (Knight and Harrison, 2018) and calculated the water balance and water mass budgets of rock glaciers (Krainer and Mostler, 2002). Other recent work has examined the morphometry, internal properties (Roer and Nyenhuis, 2007; Onaca et al., 2013; Emmert and Kneisel, 2017) and dynamic behaviour of rock glaciers (Konrad et al., 1999; Ødegård et al., 2003; Janke, 2005; Jansen and Hergarten, 2006; Serrano et al., 2010; Müller et al., 2016; Anderson et al., 2018), their sediment sources and transport capacity (Barsch and Jakob, 1998; Humlum, 2000; Humlum et al., 2007), and hydrology (Schrott, 1996; Krainer and Mostler, 2002; Geiger et al., 2014; Rangecroft et al., 2015). Despite these varied foci of rock glacier research, the relationships of rock glaciers to other mountain landforms, and their evolution over time and space, are still poorly known, conceptually and in field contexts (Johnson, 1983; Janke et al., 2015; Knight and Harrison, 2018). This study contributes to this emerging debate on rock glaciers and their morphodynamic significance in deglacierizing

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mountains by considering (i) the relationships of rock glaciers to glacial, periglacial, and paraglacial environments and processes and (ii) specific examples of rock glaciers in the Nepalese Himalayas that illustrate the varied geomorphic settings in which they can develop and with implications for long-term mountain landscape evolution. A key conclusion of this study is that not all rock glaciers exhibit the same sensitivity to climate forcing, depending on their genetic origin(s), and that glaciological versus slope versus climatic controls on rock glacier evolution vary through the rock glacier life cycle. This means that different rock glaciers cannot be compared uncritically to one another or used as equivalent sources of information when it comes to comparing the geomorphology or climatic evolution of different mountain regions worldwide.

2. Methodology and approach

The first part of this study is conceptual and is based upon a critical analysis of previous work on rock glaciers, supplemented by observations by the authors from active and relict rock glaciers worldwide, including in Europe, South America, and the Himalayas. The second part of this study is based on new remote sensing and field evidence from the Khumbu area of the Nepalese Himalayas, which focuses on mapping the distribution and extent of rock glaciers in the region and on understanding the relationship between debris-covered glaciers and rock glaciers based on their formational setting and geomorphic and sedimentary properties. Rock glacier mapping was achieved using fine spatial resolution satellite image data accessed through Google Earth. Platforms used were SPOT, QuickBird, Worldview-1, Worldview-2, and IKONOS. Geomorphic mapping was done mainly by onscreen digitising and verified during fieldwork (Jones et al., 2018). The context for the second part of this study is the critical interplay between glacial, periglacial, and paraglacial (rockfall sediment supply) processes in the development and dynamics of rock glaciers in this region (e.g., Scherler et al., 2011; Jones et al., 2018), which are in turn critical for regional water supply and geohazard risk (Immerzeel et al., 2010; Kraaijenbrink et al., 2017).

3. Rock glaciers: Environmental domains and evolutionary relationships

The different origins of rock glaciers have been debated for several decades (e.g., Barsch, 1977; Martin and Whalley, 1987; Berthling, 2011). Many rock glaciers can be viewed as polygenic landforms formed mainly during ice retreat (deglacial) phases in deglacierizing mountains, although they are also known to form in nonglacial, periglacial environments (Hamilton and Whalley, 1995). As a result, several different classification schemes of rock glaciers have been identified based on their morphology, dynamic behaviour, geomorphic setting, or some combination of these properties (Martin and Whalley, 1987; Hamilton and Whalley, 1995). For example, Johnson (1984) classified rock glaciers into simple glacial and nonglacial types, influenced by high-magnitude geomorphic events. Giardino and Vitek (1988) identified rock glaciers as transitional landforms of glacial or periglacial types, evolving from debris from glaciers or slopes, and evolving to moraines and slope deposits respectively. Janke et al. (2015) classified rock glaciers into three types, derived from variations in ice content evaluated using remote sensing methods. In summary, different rock glacier classification schemes exist but these are usually mutually exclusive, applied to only a single area or region, and examine different combinations of physical or dynamical properties. To better integrate these ideas together, Table 1 shows examples of rock glaciers formed in different environmental domains, or formed or controlled by a set of processes associated with that particular environmental domain. Although largely polygenic, most rock glaciers reported in the literature are dominated by certain sets of processes, which may reflect their evolutionary history or dominant regional climate regime (Giardino and Vitek, 1988). The classification scheme adopted here builds from Humlum (1988), who distinguished between rock glaciers of dominantly glacial origin (controlled by snow accumulation) and periglacial origin (controlled by ground temperature) (e.g., Ishikawa et al., 2001). Here, we add a further category, which describes rock glaciers of dominantly paraglacial origin, controlled by increased slope sediment supply during regional deglaciation. Rock glacier development in these three different environmental domains is now examined.

Table 1
Examples of rock glaciers that have formed from a certain dominant overall environmental domain or set of processes associated with that environmental domain.

Dominant genetic origin of rock glacier	Example location	Reference source
Glacial (by debris burial of glacial ice)	Yukon, USA	Johnson, 1980
	Stubai Alps, Austria	Krainer and Mostler, 2000
	Upper Valtellina, Italian Alps	Guglielmin et al., 2004
	Tröllaskagi, Iceland	Lilleøren et al., 2013
	Andes, central Chile	Monnier and Kinnard, 2015
	Andes, central Chile	Janke et al., 2015
Periglacial (by development of permafrost)	Vanoise Massif, French Alps	Monnier et al., 2013
	Ötzal Alps, Italian Alps	Krainer et al., 2015
Paraglacial (by development of talus slope deposits)	Yukon, USA	Johnson, 1984
	West Greenland	Humlum, 2000
	Sierra Nevada, USA	Millar et al., 2013
	Svalbard	Hartvich et al., 2017

3.1. Glacial origins

Rock glaciers can be formed at a valley glacier terminus by upward shearing of subglacial sediments followed by ice stagnation; coverage of the ice surface by supraglacial debris derived from valley sides; ice stagnation and downwasting leading to increased sediment concentration within the remaining ice; and by transformation of ice-cored moraines by mass movements or melting of internal ice, resulting in increased sediment concentration. Rock glaciers therefore usually develop at the onset of glacier retreat or stagnation, and at the front of valley glaciers, and are thus found in particular temporal and spatial contexts. In this environmental setting, rock glaciers mimic a valley glacier terminal moraine. Notably, rock glaciers do not develop at the termini of larger ice caps or ice sheets, largely because of a lack of adequate sediment supply. In the NW European Alps, glacier-derived rock glaciers have developed as a result of rockfalls onto steep glacier surfaces, and this is confirmed by electrical resistivity tomography (ERT) profiles (Bosson and Lambiel, 2016). Here, ablation rates beneath the debris cover are around 40 times lower than on adjacent debris-free areas of the glacier surface, amplifying rock glacier response under conditions of climate warming and glacier thinning. Similar patterns are observed in eastern Nepal where rock glaciers have evolved from inactive glaciers, particularly at the transition zone to discontinuous permafrost (Ishikawa et al., 2001). In the Andes of central Chile, the transition from glaciers to rock glaciers is dependent on supraglacial debris thickness, and thus the morphodynamic distinction between these types is related to whether surface debris has vertical and horizontal velocities different to those of the underlying glacier (Janke et al., 2015). This definition of a glacial ice-derived rock glacier also holds for examples from Yukon, USA (Johnson, 1980).

3.2. Periglacial origins

The most common genetic origin reported for rock glaciers globally is in association with the periglacial environmental domain and linked to the development, maintenance, and seasonal dynamics of permafrost and the active layer. Many studies suggest that the lowermost