Geomorphology 204 (2014) 61–70

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Lightning as a geomorphic agent on mountain summits: Evidence from southern Africa

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ARTICLE INFO

Article history:
Received 24 January 2013
Received in revised form 13 May 2013
Accepted 25 July 2013
Available online 8 August 2013

Keywords:
Lightning strikes
Debris production
Periglacial processes
Mountains
Frost shattering
Lesotho

ABSTRACT

The presence of angular bedrock-derived debris on mountain summits worldwide has usually been associated with present or past periglacial frost shattering, thermal fracturing and other climatically-mediated weathering processes. Climatic inferences are commonly made based on such geomorphological evidence, even if frost shattering and other processes are unlikely under present climatic conditions. This paper questions this assumed genetic link between present/past climate and production of angular bedrock-derived debris by describing the geomorphological impacts of lightning strikes on exposed mountain summits. Using examples from the high Drakensberg of eastern Lesotho, southern Africa, the impacts of lightning strikes are described, which include the generation of angular, fractured bedrock-derived debris. These impacts are identified in the field based on clear and unambiguous criteria that can be used to distinguish between lightning-induced weathering processes and those processes associated with 'more typical' alpine weathering. This paper argues that lightning strikes are an important geomorphic agent of, in particular, low-latitude mountain summits, and that to make uncritical climatic inferences based on the presence of 'frost shattered debris' on mountain summits is wholly erroneous.

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1. Introduction

The geomorphological evolution and morphological properties of mountain landscapes worldwide have been most commonly linked to weathering and erosion processes under glacial, paraglacial and periglacial climatic regimes (Owens and Slaymaker, 2004; Knight and Harrison, 2009). Although glacierised mountains have the highest rates of sediment yield into outflowing rivers (e.g., Brardononi et al., 2009; Schiefer et al., 2010; Van den Berg and Schlunegger, 2012), subaerial weathering and erosion processes typical of cold, non-glacial (periglacial) environments are geomorphologically more significant because they operate on larger spatial scales and longer time scales than glacial processes alone (Pawelec, 2011; Verleysdonk et al., 2011). As such, the geomorphology of mountain summits is most commonly viewed as a product of past and/or present periglacial weathering and erosion (e.g., Nelson et al., 2007; Goodfellow et al., 2009; Ballantyne, 2010; Hall and Thorn, 2011). The physical (mechanical), chemical and biological weathering processes most commonly cited as important in periglacial environments are, in no particular order, frost shattering through ice crystal growth (gelivation), porewater migration, thermal expansion, and biochemical dissolution (formation of tafoni) (e.g., Hoch et al., 1999; Hall and André, 2001; Matsuoka, 2001; Boelhouwers, 2004; Egli et al., 2004; Sumner et al., 2004; Darmody et al., 2005; Dixon and Thorn, 2005; Hall and Thorn, 2011; Matthews and Owen, 2011; Hall et al., 2012). The unifying theme of these weathering processes is that their occurrence and rate of operation are strongly climatically-mediated (Rea et al., 1996; Boelhouwers, 2004; Paasche et al., 2006). The relative importance of each process at any one location, and the interplay between processes, depends on the absolute values and the diurnal/seasonal ranges of temperature, precipitation and relative humidity. These variables, their interplay and relative importance also change with respect to elevation, rock type, aspect, soil/snow cover and other antecedent, environmental and edaphic factors (André, 2003; Egli et al., 2006).

Views of the relationship between climate and development of mountain summit geomorphology have recently been informed by studies that have examined independent lines of evidence for the longevity, and thus climatic control, of summit geomorphological features, in particular blockfields. For example, the presence of gibbsite and other minerals within mountain summit soils and sub-blockfield weathering profiles has been used as an indicator of long-term subaerial weathering under variable and warm past climatic regimes (e.g., Marquette et al., 2004; Paasche et al., 2006; Munroe et al., 2007; Goodfellow et al., 2009; Strømsøe and Paasche, 2011; Betard, 2012). The preservation of such weathering products on mountain summits has been used as evidence to suggest that these summits were not glaciated during the late Quaternary (Ballantyne et al., 1998), or that mountain summits were preserved beneath cold-based ice (Kleman et al., 1999). Supporting evidence for such partial preservation of mountain summit geomorphology over one or more glacial cycles comes mainly from cosmogenic dating of intact bedrock surfaces (not loose surface boulders). These studies show that adjacent rock surfaces can have markedly different radiometric ages (Stroeven et al., 2002; Goodfellow et al., 2008), and thus that the effects of glacial erosion in shaping the macro-scale geomorphology of mountain summits have high spatial variability

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0169-555X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2013.07.029

(Kleman and Borgström, 1996; Kleman et al., 1999). Collectively, the evidence from weathering minerals and cosmogenic ages shows that the development and preservation of mountain summit geomorphology does not follow a single climate forcing–response relationship, and thus the presence of certain summit geomorphological features cannot be used uncritically as palaeoclimatic indicators (Fjellanger et al., 2006).

Although the role of climatically-mediated weathering processes contributing to the formation of mountain geomorphology has been recently questioned (Hall et al., 2012), the prevailing view is that climate is the primary driving factor for all physical, chemical and biotic weathering processes that affect all exposed land surfaces (Dixon and Thorn, 2005; Hall and Thorn, 2011). This relationship is one founded on decades of observational-based research on different scales and in different climatic, altitudinal and geomorphic settings (Hall et al., 2012). Apart from cryospheric (glacial and periglacial) processes themselves, it is usually assumed that the geomorphological evolution of mountain summits results from subaerial physical (mechanical) and chemical weathering under a cold-climate regime (Hoch et al., 1999; Hall et al., 2002; Darmody et al., 2005; Nicholson, 2008; Matthews and Owen, 2011), in particular through the process of frost shattering (Matsuoka, 2001; Matsuoka and Murton, 2008). Evidence for this prevailing viewpoint comes mainly from the presence of angular detached bedrock debris that is found across mountain summits worldwide and which forms block fields on plateaus and screes/talus cones and fans mantling steep bedrock slopes (e.g., Ballantyne, 1998; Boelhouwers, 2004; Ballantyne, 2010). Generation of this angular surficial debris is important because it provides the raw materials that can be moved by glacial, periglacial and slope processes to form moraines, rock glaciers, blockfields, block streams, debris lobes or cones, and contribute to downslope sediment supply and the formation of solifluction lobes and valley-fills (Grab, 1999; Boelhouwers et al., 2002; Slaymaker et al., 2003; Sumner, 2004; Gordon and Ballantyne, 2006). This paradigm of climatically-mediated mountain weathering processes is an important tenet of palaeoclimate reconstruction in mountain environments worldwide (e.g., Hall et al., 2002; Nelson et al., 2007).

Whilst the role of cold-climate weathering is certainly of global importance in mountain geomorphology, low-latitude mountains in particular are affected by another significant geomorphic agent, namely lightning strikes. The aim of this paper is to examine the role of lightning strikes in the formation of angular, bedrock-derived mountain summit debris which, geomorphically, looks very similar to 'frost-shattered debris'. The paper briefly reviews the processes by which lightning occurs over mountain blocks and the surface evidence for lightning strikes (Section 2). This provides the context for describing the regional geological and climatic setting of the study area (Fig. 1) in the high Drakensberg of eastern Lesotho, southern Africa (Section 3), methods of data collection and analysis used in this study (Section 4.1), and the criteria used to distinguish unequivocally between the agencies of lightning and more typical cold-climate mountain weathering processes in the formation of angular, bedrock-derived mountain summit debris (Section 4.2). The paper then describes field evidence for lightning strikes (Section 5), and discusses the implications of this evidence for the geomorphic evolution of mountain summits and the climatic interpretation of such apparent 'frost-shattered angular debris' (Section 6). A critical outcome of this study is that lightning strikes have been neglected as a geomorphic agent in mountains, and that the viewpoint that mountain summit debris is produced dominantly by past or present frost-shattering and other climatically-mediated processes is erroneous.

2. Climatology and effects of lightning strikes on mountains

Over land, cloud-to-ground lightning strikes are most common where warm air masses rise orographically up a mountain front, resulting in atmospheric instability, latent heat release, and thundercloud development (Christian et al., 2003; Williams, 2005). Thunder, lightning and heavy rain are therefore commonly triggered over or around mountain blocks, particularly during summer months. Cloud-to-ground strike rates in the order of <150 strikes $\text{km}^{-2}\ \text{yr}^{-1}$ are recorded across many low latitude (15°N–30°S) continental areas of Africa, southern and central Asia, central America and southeast USA (Christian et al., 2003; Collier et al., 2006). As storm clouds develop, a positive electrostatic charge of water molecules progressively accumulates at the top of the cloud, with a negative charge at the base of the cloud. Cloud-to-ground lightning takes place as the negatively-charged lower cloud is discharged against the positively-charged ground surface. Fig. 2 shows an example of a lightning strike impacting on the ground surface in eastern Lesotho. Uniquely, this photo captures a bright blast generated directly by the lightning strike at the moment of impact. The very short time duration of lightning strikes means that this bright blast, coinciding with the lightning flash making contact with the ground surface, cannot be a post-event fire. The bright blast is therefore interpreted as an explosive event taking place on the ground surface at the very moment and location of strike impact.

Generally, lightning strike frequency increases with increased land surface elevation (i.e., mountain height) but declines with elevation above around 1500–1800 m (Bhavika, 2007), and shows strong seasonal and diurnal patterns related to the timing of the most intense convective storms (Rivas Soriano et al., 2005; Collier et al., 2006; Santos et al., 2012). The electrical current produced by most cloud-to-ground lightning strikes is highly variable, from 10 kA to 300 kA (Verrier and Rochette, 2002; Wakasa et al., 2012) with an instantaneous ground surface heating of up to 30,000 °C over a time period of ~<1 ms (Grapes and Müller-Sigmund, 2010). Such conditions can cause instantaneous heating and expansion of air and moisture on and within the ground surface, and can yield a range of physical impacts. The most common physical impacts of lightning strikes on exposed rock surfaces include:

- Incineration of organic materials on the rock surface (Appel et al., 2006);
- Formation of fulgurite (Pasek et al., 2012) through very rapid selective melting and fusion of pre-existing minerals within host rocks, or formation of new minerals (Rietmeijer et al., 1999; Grapes and Müller-Sigmund, 2010). Fulgurite can also form within loose sediments or thin soils above the rock surface (Navarro-González et al., 2007; Longinelli et al., 2012);
- Formation of localised geomagnetic anomalies developed within the rocks' minerals (Cox, 1961; Graham, 1961; Beard et al., 2009). This arises from the selective melting and subsequent cooling of pre-existing minerals within the host rock (see previous bullet point), with an induced contemporary remanent magnetic field being superimposed upon the regional geomagnetic background (Sakai et al., 1998; Verrier and Rochette, 2002; Beard et al., 2009). On a mesoscale, the induced field can be readily identified using a magnetometer, and can extend spatially over $<20\ \text{m}^2$ (S. Webb, pers. comm., 2012). On a microscale, the induced field can be identified using a compass. When the compass is slowly moved over the bedrock surface, the induced field will reorientate the compass needle away from the regional background field. The degree of reorientation reflects the strength of the induced field, which is highest at the position of the lightning strike. In extreme cases, the compass needle spins quickly through 360° and over a distance of a few cm around the position of the lightning strike;
- 'Explosive blasting' of intact rock surfaces caused mainly by very rapid heat-expansion of air and/or moisture on the rock surface, within the rock matrix, or within cracks or fractures (Barnett, 1908; Knight, 2007; Wakasa et al., 2012; see Fig. 2). Pre-existing cracks or fractures can be widened or new cracks developed. 'Explosive blasting' of rocks is the primary mechanism by which angular bedrock-derived debris can form (Knight, 2007);
- Formation of pits or enclosed depressions within a boulder or blockfield, in which weathered, lichen-covered boulders have been moved some metres of distance away from the pit centre, revealing

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