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Review

A review of topographic controls on moraine distribution

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ABSTRACT

Ice-marginal moraines are often used to reconstruct the dimensions of former ice masses, which are then used as proxies for palaeoclimate. This approach relies on the assumption that the distribution of moraines in the modern landscape is an accurate reflection of former ice margin positions during climatically controlled periods of ice margin stability. However, the validity of this assumption is open to question, as a number of additional, nonclimatic factors are known to influence moraine distribution. This review considers the role played by topography in this process, with specific focus on moraine formation, preservation, and ease of identification (topoclimatic controls are not considered). Published literature indicates that the importance of topography in regulating moraine distribution varies spatially, temporally, and as a function of the ice mass type responsible for moraine deposition. In particular, in the case of ice sheets and ice caps (>1000 km^2), one potentially important topographic control on where in a landscape moraines are deposited is erosional feedback, whereby subglacial erosion causes ice masses to become less extensive over successive glacial cycles. For the marine-terminating outlets of such ice masses, fjord geometry also exerts a strong control on where moraines are deposited, promoting their deposition in proximity to valley narrowings, bends, bifurcations, where basins are shallow, and/or in the vicinity of topographic bumps. Moraines formed at the margins of ice sheets and ice caps are likely to be large and readily identifiable in the modern landscape. In the case of icefields and valley glaciers (10–1000 km^2), erosional feedback may well play some role in regulating where moraines are deposited, but other factors, including variations in accumulation area topography and the propensity for moraines to form at topographic pinning points, are also likely to be important. This is particularly relevant where land-terminating glaciers extend into piedmont zones (unconfined plains, adjacent to mountain ranges) where large and readily identifiable moraines can be deposited. In the case of cirque glaciers (<10 km^2), erosional feedback is less important, but factors such as topographic controls on the accumulation of redistributed snow and ice and the availability of surface debris, regulate glacier dimensions and thereby determine where moraines are deposited. In such cases, moraines are likely to be small and particularly susceptible to post-depositional modification, sometimes making them difficult to identify in the modern landscape. Based on this review, we suggest that, despite often being difficult to identify, quantify, and mitigate, topographic controls on moraine distribution should be explicitly considered when reconstructing the dimensions of palaeoglaciers and that moraines should be judiciously chosen before being used as indirect proxies for palaeoclimate (i.e., palaeoclimatic inferences should only be drawn from moraines when topographic controls on moraine distribution are considered insignificant).

1. Introduction

Glacial landforms are a fundamental source of information about the extent and dynamics of former glaciers and ice sheets (Dyke and Prest, 1987; Kleman and Borgström, 1996; Clark, 1997; Kleman et al., 1997, 2006). Many studies are undertaken with the express purpose of obtaining palaeoclimatic data from these landforms through the reconstruction of former ice-mass dimensions (e.g., Sutherland, 1984; Benn and Ballantyne, 2005). By far the most useful and widely used landforms for this purpose are ice-marginal moraines, which provide direct evidence of former ice margin positions (see Dyke and Prest, 1987; Svendsen et al., 2004). In providing this information, the modern distribution of ice-marginal moraines has effectively been used as an indirect proxy for palaeoclimate (e.g., Benn and Ballantyne, 2005; Ballantyne et al., 2007). However, the validity of this approach is open to question as a number of additional, nonclimatic factors are known to influence moraine formation (see Mercer, 1961; Funder, 1972, 1989; Punkari, 1980; Warren and Hulton, 1990; Warren, 1991; Kessler et al., 2006; Kaplan et al., 2009; Pratt-Sitaula et al., 2011; Anderson et al., 2012; Barr and Clark, 2012b), preservation (see Putkonen and O'Neal, 2006;

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Anderson et al., 2012; Kirkbride and Winkler, 2012), and ease of identification (see Barr and Clark, 2012b). Perhaps the most important of these factors is topography, which can lead the modern distribution of moraines to 'appear to carry palaeoclimatic significance which it does not have' (Warren, 1991, p. 14). Despite this importance, the role of topography in regulating the distribution of moraines is rarely explicitly addressed in palaeoglaciological reconstructions (i.e., moraines are often directly dated and used to infer former ice margin positions without consideration of landform origin or topographic context). The aim of this review is to address this shortcoming and to encourage critical discussion by focusing specifically on the role played by topography in regulating moraine formation, preservation, and ease of identification. This paper is primarily a review of published literature and is divided into four sections: (i) a background to ice-marginal moraines and their use in palaeoclimate reconstructions; (ii) a consideration of topographic controls on moraine formation; (iii) a consideration of topographic controls on moraine preservation and ease of identification; and (iv) an assessment of the implications that topographic controls on moraine distribution have for palaeoglacier and palaeoclimate reconstructions. This paper focuses on ice-marginal moraines, though much of the material also applies to other associated landforms, such as controlled or hummocky moraines (see Lukas, 2005; Evans, 2009).

2. Background

2.1. Moraine properties

Ice-marginal moraines are ridge-like formations, which are typically classified according to their location as either end (deposited around glacier termini), lateral (deposited along glacier lateral margins), or latero-frontal (Fig. 1). They are formed through a number of processes, as supra-, en-, and subglacial debris is dumped at glacier margins (Eyles, 1983; Benn, 1992); proglacial debris is bulldozed during advance (see Boulton, 1986; Bennett, 2001); subglacial sediment is squeezed from beneath glacier margins (see Price, 1970); and bedrock and unconsolidated sediments are thrust into imbricate ridges during ice advance (see Evans and England, 1991; Hambrey and Huddart, 1995). Individual moraine ridges are often produced through a combination of these processes and can form subaerially and subaqueously (see Krzyszkowski and Zeliński, 2002; Ottesen and Dowdeswell, 2006). The internal structure and composition of ice-marginal moraines is largely determined by their mode of formation and is therefore highly variable. Some are almost entirely composed of glacial diamicton, whilst others contain a variety of glacigenic and glaciofluvial materials, often preserving sedimentary and/or deformation structures (see Boulton et al., 1999; Evans, 2009). A key factor in moraine formation is that debris must accumulate at glacier margins. This debris is typically transported englacially or supraglacially (though proglacial sediment can also be bulldozed), and the volume of material available for moraine formation therefore depends on ice velocity, the volume of debris within/upon a glacier, and the duration of ice margin stability (i.e., still-stand duration) (Andrews, 1972; Kirkbride and Winkler, 2012). For this reason, conditions that favour the formation of large moraines are often found at the margins of dynamic and erosive (temperate) glaciers which are able to entrain/accumulate large quantities of debris, but which also occupy stable positions for prolonged periods (Spedding and Evans, 2002; Swift et al., 2002; Cook and Swift, 2012). The largest ice-marginal moraines are 100s of kilometres long and 10s of kilometres wide (Fig. 2). Some have an altitudinal-range (relief) of hundreds of metres, whilst others show very little topographic expression (Barr and Clark, 2012a, b). Though margin stability is likely to encourage the development of large moraines, Anderson et al. (2014) demonstrated that 20-m-high examples can form in <20 years; and in front of modern surge-type glaciers, the formation of similarly sized end moraines can occur in a matter of days (Benediktsson et al., 2008).

2.2. Moraines as indicators of palaeoclimate

Ice-marginal moraines are ubiquitous in glaciated landscapes (e.g., Heyman et al., 2008; Lovell et al., 2011; Fredin et al., 2012), with some of the largest known examples deposited by the vast ice sheets that occupied North America and northern Europe during the Last Glacial Maximum (LGM) (Fig. 2A–B). Some of the oldest moraine sequences on Earth date back over 1 Ma (Singer et al., 2004; Kaplan et al., 2009) (Fig. 2C); and the global population of offshore examples is significant, and expanding (e.g., Bradwell et al., 2008; Spagnolo and Clark, 2009; Winsborrow et al., 2010). Sedimentological and morphometric analyses of moraines provide information about former glacier flow dynamics, thermal regime, and debris content (amongst other factors) (see Boulton, 1986; Lukas, 2005; Evans, 2009), but moraines are most commonly used simply as indicators of former ice margin positions (e.g., Svendsen et al., 2004; Fredin et al., 2012). On the assumption that fluctuations in ice margins are driven by variations in climate (Oerlemans et al., 1998; Dyurgerov and Meier, 2000; Putnam

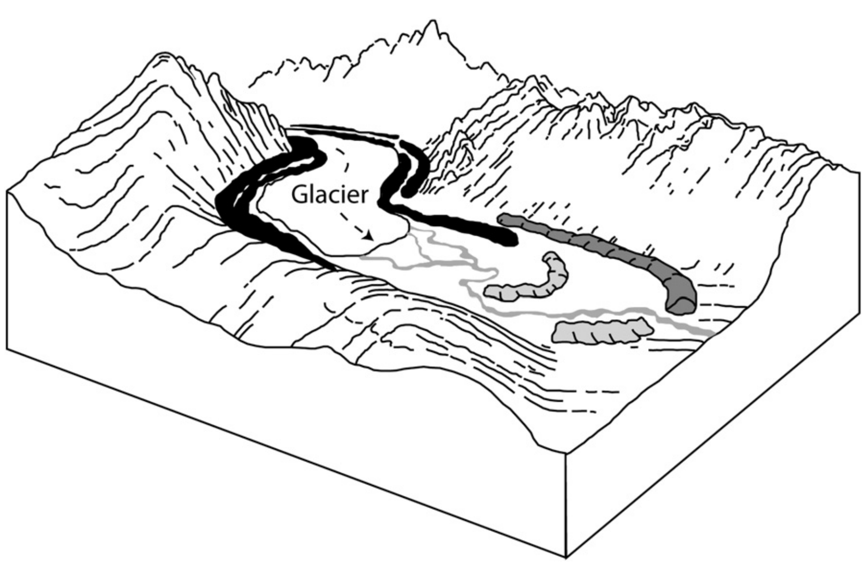

Fig. 1. Schematic illustration of end moraines (light grey), lateral moraines (black), and latero-frontal moraines (dark grey) formed by a valley glacier. The dashed arrow shows ice-flow direction.
Image modified from Huber (1987).