Geomorphology 194 (2013) 25–33

Contents lists available at SciVerse ScienceDirect

Geomorphology

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

Digital surface models are not always representative of former glacier beds: Palaeoglaciological and geomorphological implications

Andrew Finlayson *

British Geological Survey, Murchison House, West Mains Road, Edinburgh EH93LA, UK
Institute of Geography, University of Edinburgh, Edinburgh EH89XP, UK

ARTICLE INFO

Article history:
Received 8 October 2012
Received in revised form 27 March 2013
Accepted 28 March 2013
Available online 4 April 2013

Keywords:
Digital surface models
Palaeoglaciology
Glacier profile
Calving
Drumlins

ABSTRACT

Quantitative palaeoglaciological studies that use digital surface models (DSMs) may be subject to error because former glacier beds are not always accurately represented. This is because the Earth's surface may have changed significantly since deglaciation. This paper evaluates some of the potential errors caused by postglacial sedimentation, by comparing the results of physical palaeoglaciological reconstructions and bedform morphometric analyses in parts of Scotland, using both the modern land surface and interpolated former glacier beds derived from borehole data. For a former terrestrial outlet glacier, removal of postglacial sediments increases the modelled ice surface elevation and ice thickness by 0.7% and 5%, respectively, over a 27-km flow line. For a former tidewater glacier, the reconstructed steady state ice flux is increased by 250% when the modern land/seabed surface is replaced with an interpolated former glacier bed. In a classical drumlinised landscape, removal of postglacial sediments affects bedform morphometrics, with an increase in measured drumlin length, width, relief, and volume. The cases presented in this paper are from environments known to have experienced postglacial sedimentation. They provide situational examples of the degree of error that can be introduced when the modern land surface is used to represent former glacier beds in these environments. In some regions, sufficient subsurface data exists over large areas to create improved topographic representations of former glacier beds; these could form important inputs to the next generation of palaeo-ice-sheet and palaeo-glacier simulations.

1. Introduction

Digital surface models (DSMs) can provide high resolution geomorphological information about the Earth's surface. They are used to represent past glacier beds for the reconstruction of former ice sheets (Lidmar-Bergstrőm et al., 1991; O'Cofaigh et al., 2009; Trommelen and Ross, 2010), numerical palaeo-glacier simulations (Plummer and Phillips, 2003; Golledge et al., 2008) and statistical analyses of glacier bedform morphometrics (Dunlop and Clark, 2006; Clark et al., 2009; Hess and Briner, 2009). When using DSMs, geomorphologists have to assess the risk of any land surface change, in the time between glacier ice occupation and capture of elevation data, having affected the geomorphic expression of the former glacier bed. Commonly, these changes are too small to introduce significant error to conceptual palaeoglaciological reconstructions. However, the importance of bed topography to numerical simulations and quantitative morphometric assessments could make them prone to errors if the land surface has been considerably lowered by erosion or raised by sediment deposition after glacier retreat. In lowland and coastal areas, high rates of sedimentation have been shown to accompany, and immediately follow, deglaciation (Eyles et al., 1990; Cowan and Powell, 1991; Leventer et al., 2006), and some workers have recognised that sediment laid down after ice margin retreat (hereafter referred to as postglacial sediment) may lead to errors in quantitative studies (Piotrowski and Tulaczyk, 1999; Golledge et al., 2012; Spagnolo et al., 2012). The goal of this paper is to test how the results of simple quantitative palaeoglaciological investigations differ when the topographic expression of postglacial sediments is removed from DSMs, thereby providing some indication of the error for a given set of examples.

Three case studies from parts of Scotland that were deglaciated ca. 15 ka BP (Fig. 1A) are presented. Reconstructed glacier characteristics and bedform morphometric analyses obtained using the modern land surface are compared with those derived from interpolated former glacier beds based on densely spaced borehole data. The first case considers differences in valley shape and the effects on a glacier surface profile calculated using an iterative flowline model in the Clyde basin, west-central Scotland (Fig. 1B). The second case examines the differences in reconstructed calving rates and hypothetical ice fluxes at a former tidewater glacier margin in the Cromarty Firth, northeast Scotland (Fig. 1C). The third case compares three-dimensional morphometric measurements for a small sample of

* British Geological Survey, Murchison House, West Mains Road, Edinburgh EH93LA, UK. Tel.: +44 131 650 0209; fax: +44 131 668 1535.
E-mail address: afin@bgs.ac.uk.

0169-555X/$ – see front matter
http://dx.doi.org/10.1016/j.geomorph.2013.03.026

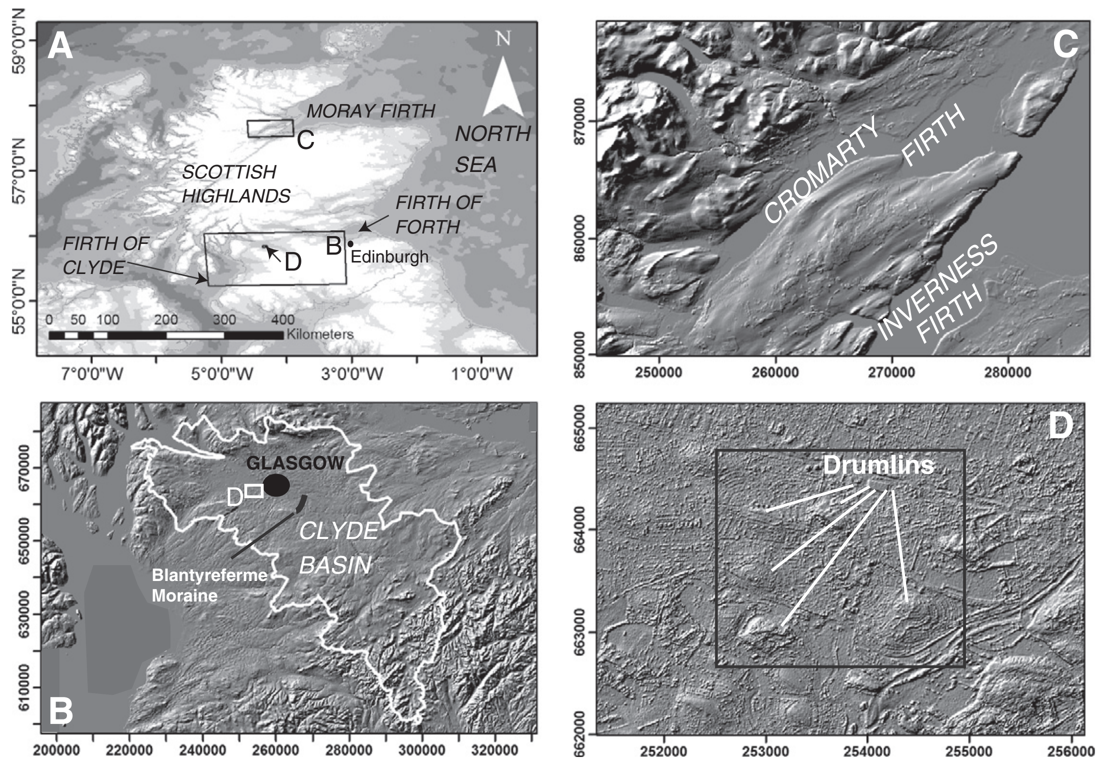

Fig. 1. (A) Location of case study sites within national context. (B) Clyde basin, west-central Scotland. White line marks the area included in the geological model described in Finlayson (2012). (C) Cromarty Firth, northeast Scotland. (D) Drumlinised terrain in southwest Glasgow. Images derived from ETOPO1 Global Relief Model (A) and Intermap Technologies NEXTMap Britain elevation data (B, C, D). Coordinates in B, C, and D in British National Grid.

drumlins in southwest Glasgow (Fig. 1D). The examples are chosen from near-coastal areas known to have been subjected to postglacial sedimentation. Such environments are often included in palaeoglaciological studies, and coastal margins are recognised as key dynamic zones of past ice sheets. Therefore a requirement exists to quantitatively evaluate potential errors that may be introduced into palaeoglaciological models and bedform measurements by unrepresentative DSMs in these areas.

2. Study area and methods

2.1. Clyde basin: valley shape and former glacier profile

The first study focuses on valley shape and reconstructed glacier surface profile in the Clyde basin, west-central Scotland (Fig. 1B) at the time when the Blantyreferme moraine was formed. During overall ice sheet retreat, the Blantyreferme moraine was constructed in the lower part of the Clyde basin by an outlet glacier, sourced from an ice cap centred over the Scottish Highlands (Price, 1975; Finlayson et al., 2010). Glacier flow at that time was toward the southeast. Final glacier decay in the lower Clyde basin was accompanied by relative sea level rise to almost 40 m above present when thick sequences of glaciomarine silts and clays were laid down, partially masking the former glacier bed (Browne and McMillan, 1989; Peacock, 2003).

In the Clyde basin, the former glacier bed was extracted from the three-dimensional geological model described by Finlayson (2012). The model (Fig. 2A) adheres to the surface sediment distribution shown on 1:50,000-scale geological maps and subsurface data derived from 1260 borehole logs (Fig. 2B). It comprises a series of surfaces, representing the tops and bases of lithostratigraphic units, derived through triangulation of regularly spaced x, y, z nodes along cross sections (total length 1860 km) and 'envelopes,' which represent the lateral (surface and buried) extent of lithostratigraphic units. The model was calculated at a 500-m grid resolution. Postglacial lithostratigraphic units, representing 2.37 km^3 of sediment, were removed to obtain an interpolated glacier bed, more closely representing bed topography at the time when the Blantyreferme moraine was formed (Fig. 2C). The interpolated former glacier bed is overdeepened and lies below the postglacial and modern sea level. The depth of the interpolated bed is therefore unlikely to have been enhanced by postglacial fluvial erosion.

The influence of postglacial sediments on glacial valley shape was examined in the lower part of the Clyde basin, using valley shape factor (f). Shape factor is used to account for the part of a glacier's weight that is supported by the valley sidewalls; it defines the proportion of driving stress (τ_D) that is transferred to basal shear stress (τ_B) at the valley centre, so that $\tau_B = f\tau_D$. Driving stress is calculated from

$$\tau_D = \rho_I g H \tan\alpha \tag{1}$$

where ρ_I is the density of glacier ice (~900 kg m^{-3}), g is the gravitational acceleration (9.81 m s^{-2}), H is the glacier thickness (m) and α is the glacier surface slope. For a flat bed (which presents no side drag), $f = 1$, and for a semi-ellipse-shaped valley with a half-width equal to centre-line ice thickness $f = 0.5$ (Paterson, 1994). Shape factor can be calculated from

$$f = \frac{A}{HP} \tag{2}$$

where A is the cross-sectional area of the valley that is filled with glacier ice, and P is the cross-sectional perimeter that is in contact with the glacier ice. The approach adopted here is that used by Benn and Hulton (2010) in which A is calculated along the cross section from

$$A = \sum_{i=1}^{n} \frac{\left((B_{MAX} - B_i) + (B_{MAX} - B_{i+1})\right)\Delta y}{2} \tag{3}$$