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Modelling North American palaeo-subglacial lakes and their meltwater drainage pathways

Stephen J. Livingstone [a,*], Chris D. Clark [a], Lev Tarasov [b]

[a] Department of Geography, Sheffield University, Sheffield, UK
[b] Department of Physics and Physical Oceanography, Memorial University of Newfoundland and Labrador, Canada

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ABSTRACT

This paper presents predictions of palaeo-subglacial lakes and their drainage pathways beneath the North American Ice Sheet during the last glaciation. We utilise data on the current topography and seafloor bathymetry, and elevation models of the ice- and ground-surface topography from data-calibrated glaciological modelling to calculate the hydraulic potential surface at the ice-sheets bed. Given that specific ice-surface elevations are only known from modelled outputs, and thus contain significant uncertainty, we utilise many such outputs to examine where on the bed that subglacial lakes are likely to have occurred. Our analysis demonstrates the potential for subglacial lake genesis, particularly beneath the former Cordilleran Ice Sheet; along the suture zone between the Laurentide and Cordilleran ice sheets; in Hudson Bay; in the Great Lake basins and deep trenches of the Canadian Archipelago. During the Last Glacial Maximum we suggest that at least 1000 km^3 of meltwater could have been stored subglacially. As the ice-sheet and the bed evolved subglacial lakes repeatedly formed and emptied, particularly in Hudson Bay and the suture zone between the Laurentide and Cordilleran ice sheets where lakes were characteristically broad and shallow (< 10 m deep). In contrast, the Cordilleran Ice Sheet was characterised by deep (up to ~90 m) and persistent lake genesis. Significantly, similar distributions and modes of predicted subglacial lakes are obtained irrespective of the model or model run, which suggests the results are robust. Subglacial meltwater drainage varied between stable networks, typically associated with strong topographic controls, and convoluted networks that underwent considerable dynamism, including repeated meltwater network capture. These lake likelihood predictions could usefully form targets for detailed field and remote investigations and we hypothesise and explore the potential that numerous deposits and spillways previously interpreted as arising from ice-marginal lakes may have emanated from their subglacial cousins.

1. Introduction

The generation, storage and evacuation of meltwater plays a fundamental role in modulating the behaviour of ice masses (e.g. Hubbard et al., 1995; Joughin et al., 2008; Stearns et al., 2008; Bartholomew et al., 2010). Indeed, the link between subglacial meltwater and ice streaming is well documented (e.g. Engelhardt and Kamb, 1997; Smith et al., 2007). However, the spatial and temporal form of the meltwater network at the base of the Antarctic and Greenland ice sheets is not well known. This compromises our ability to accurately model processes at the ice–bed interface. An alternative approach is to observe marine and terrestrial palaeo-ice sheet beds to discern the composite imprint of subglacial processes expressed in the geomorphological and sedimentological record. This includes meltwater channels eroded into bedrock or sediment, eskers and subglacial lake deposits. These glacial landforms can be investigated at a range of scales from detailed sedimentological analysis of individual bedforms to subcontinental-scale glacial geomorphological mapping (e.g. Prest et al., 1968; Banerjee and McDonald, 1975; Shilts et al., 1987; Gorrell and Shaw, 1991; Kleman, 1992; Clark and Walder, 1994; Punkari, 1997; Fisher et al., 2005; Kozlowski et al., 2005; Margold et al., 2011; Burke et al., 2012).

Subglacial lakes are commonplace beneath the Antarctic Ice Sheet (AIS), occurring at a range of scales in a variety of topographic, thermal and ice-dynamical settings, and comprising a significant and active component of the hydrological system (e.g. Smith et al., 2009; Wright and Siegert, 2011). It is likewise anticipated that subglacial lakes existed beneath the North American Ice Sheet (NAIS) during the Quaternary (see Livingstone et al., 2012) and therefore would have had a similar influence on ice dynamics and water flow. However, palaeo-subglacial lakes are

* Corresponding author. Tel.: +44 114222 7990.
E-mail address: s.j.livingstone@sheffield.ac.uk (S.J. Livingstone).

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rarely documented (e.g. Gjessing, 1960; Munro-Stasiuk, 2003; Christoffersen et al., 2008; Lesemann and Brennand, 2009) and typically controversial (e.g. Evans et al., 2006) in part due to difficulties in distinguishing their geological signature from proglacial (ice-marginal or ice-fed) lakes (see Livingstone et al. (2012) for a review). In contrast, meltwater channels, tunnel valleys and eskers are widely observed across the formerly glaciated bed of North America, forming intricate networks detailing the composite history of meltwater drainage and ice-sheet behaviour (e.g. Bretz, 1923; Wright, 1973; Walder and Hallet, 1979; Shilts et al., 1987; Margold et al., 2011, 2013). Nevertheless, the temporal history of these features is poorly constrained throughout the evolution of the NAIS and therefore only provides a relative appreciation of meltwater flow. It is therefore difficult to elucidate when channels and eskers formed and over what time-scales they developed. Thus, despite the wealth of data, ease of access (both remotely and in the field) and spatial coverage, disentangling the glacial meltwater history of North America is complex.

With this in mind, we use hydraulic calculations derived using an ensemble of palaeo-ice and bed topographies from thermo-mechanical ice-sheet models to simulate subglacial meltwater routeways and predict where meltwater may have ponded at the ice–bed interface. This builds upon the work of Evatt et al. (2006), who used a similar approach to predict subglacial lakes at the Last Glacial Maximum (LGM). The results are presented as a series of composite maps that allow us to evaluate (i) the broad-scale patterns of meltwater drainage and evolution; and (ii) the likelihood of subglacial lakes forming at a particular location. Meltwater drainage networks are simulated at discrete time-slices throughout the evolution of the last NAIS, which allows the spatial and temporal correlations between channels, subglacial lakes, and ice-streams to be investigated. And subglacial lake predictions provide a useful guide for detailed future field investigations and for elucidating their frequency, stability, and distribution through the ice-sheets evolution.

2. Generation of subglacial lake and meltwater drainage predictions

Three-dimensional (3D) hydraulic potential surfaces (Φ) were calculated for the bed of the NAIS during the last glaciation from current digital elevation models (DEMs) of the bed topography and seafloor bathymetry and simulated elevation models of the ice and ground surface topography, using the following equation (Shreve, 1972; Clarke, 2005):

$$\Phi = \rho_w g h_b + F \rho_i g H, \tag{1}$$

where ρ_w is the density of water (1000 kg m^{-3}); ρ_i is the density of ice (917 kg m^{-3}); g is the acceleration due to gravity; h_b is the bed elevation; and H is the ice thickness. The flotation criterion, F, is the ratio of non-local, subglacial water pressure, P_w, to the ice-overburden pressure, P_i ($F = P_w/P_i$). In reality F varies both in space and time according to the configuration of the drainage system, basal ice temperature, ice-overburden pressure and the underlying geology (Clarke, 2005). However, limited borehole observations from contemporary ice masses suggest subglacial water pressure is close to the ice-overburden pressure ($F > 0.95$, e.g. Kamb, 2001) so we assume $F \approx 1$ ($P_w = P_i$). Implicit in this assumption is that the bed was wholly warm-based and that basal melting and effective pressure were uniform. As meltwater should follow the maximum gradient of the hydraulic potential surface, simple routing mechanisms in ArcGIS were used to simulate meltwater drainage pathways and to identify hydraulic minima where water may have ponded (see Evatt et al., 2006; Siegert et al., 2007; Wright et al., 2008; Livingstone et al., 2013). To test the sensitivity of subglacial lakes and meltwater pathways to the parameter F we also used a value of 0.75 ($P_w/P_i = 0.75$).

The bed topography and seafloor bathymetry were derived from Gebco_08 data, a continuous DEM for ocean and land with a spatial resolution of 30 arc-seconds. High-resolution bathymetry data of the Great Lakes were manually added (NOAA National Geophysical Data Centre, U.S. Great Lakes Bathymetry) and the DEM was then re-gridded to 5 km cell size. Given that specific ice-surface and bed topographies are only known from modelled outputs, and thus contain significant uncertainty, we utilised many such outputs (Table 1) to examine where on the bed subglacial lakes and water drainage pathways were likely to have occurred. This includes numerical ice-sheet model data of palaeo-ice and -bed topographies from: ICE-5G (Peltier, 2004); CLIMAP (CLIMAP Project Members, 1984); GRISLI (from Álvarez-Solas et al., 2011); Glimmer-CISM (from Gregoire, 2010; Gregoire et al., 2012); and 3D-MUN Glacial Systems Model (GSM) (Tarasov et al., 2012) (see Table 1 for a summary). We also reconstructed the LGM NAIS from geological evidence (Dyke et al., 2002) by estimating ice-surface profiles along flow-lines and interpolating the data to form a 3D-surface elevation model. This was achieved using

$$h = C^{1/2} \tag{2}$$

where h is the parabolic ice-surface profile and C is a constant, which describes the overall stiffness of the flow. A value of three was chosen as a guide but with some editing of elevations so that the ice sheet resembled the multi-dome configuration reconstructed from geological evidence (Winsborrow, 2007). The ice surfaces were re-gridded at 5 km resolution and the current bed DEM corrected for isostasy using the modelled bed topography data (Fig. 1).

Most emphasis is given to 3D-MUN GSM as the model was calibrated against a large set of observational constraints, including relative sea-level data, present-day rates of surface uplift and a high resolution ice-marginal chronology derived from geological and geomorphological evidence (see Tarasov et al., 2012 and Table 1). Subglacial hydrological predictions were calculated for a sample of 10 higher probability model runs from the ensemble-based analyses of the NAIS using 3D-MUN GSM (see Tarasov et al., 2012). Basal melt rates enabled cold-bedded regions of the bed (zero basal melt) to be masked out at each time-slice (Table 1).

Predictions were calculated at 1000-yr time-slices through the evolution of the ice sheet (see Table 1 for details). These predictions were then compiled for individual ice histories (i.e. single model runs) and across all models to give an indication of subglacial lake persistence and likelihood. The depths (m) of simulated subglacial lakes (L_D) were calculated, for $F = 1$, as follows:

$$L_D = (\Phi_F - \Phi)/(\rho_w g) \tag{3}$$

where Φ_F is the hydraulic potential surface at the bed surface plus the hydraulic potential of the lake. We assumed that all lakes filled to their hydraulic potential lip. Subglacial lake likelihood maps (as per Evatt et al., 2006) were calculated for each model (run), to illustrate the lake residence time and occurrence over the range of ice-sheet geometries associated with the modelled glacial cycle.

There are a number of limitations to predicting subglacial lakes and meltwater drainage networks using the method outlined above: (i) the simplistic treatment of basal conditions (see above); (ii) the DEM includes some post-glacial filling of the true subglacial bed; (iii) the coarse resolution of the models (which is especially problematic for the orographically complex Cordilleran and for resolving smaller ice streams); (iv) none of the models include dynamic coupling between the ice and subglacial meltwater, so ice-surface flattening above subglacial lakes is not accounted for; and (v) in reality some lakes do not form in hydraulic minima, such as those created by high geothermal heat fluxes or behind frozen margins (see Livingstone et al., 2012). These are not modelled here. Despite these issues, we can have confidence in our results as the errors associated with the