Quaternary Science Reviews 189 (2018) 1–30

Contents lists available at ScienceDirect

Quaternary Science Reviews

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

Invited review

Reconciling records of ice streaming and ice margin retreat to produce a palaeogeographic reconstruction of the deglaciation of the Laurentide Ice Sheet

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ARTICLE INFO

Article history:
Received 4 October 2017
Received in revised form
15 February 2018
Accepted 5 March 2018

Keywords:
Pleistocene
Glaciation
North America
Geomorphology
Glacial
Laurentide Ice Sheet
Last Glacial Maximum
Late Glacial
Deglaciation
Ice stream

ABSTRACT

This paper reconstructs the deglaciation of the Laurentide Ice Sheet (LIS; including the Innuitian Ice Sheet) from the Last Glacial Maximum (LGM), with a particular focus on the spatial and temporal variations in ice streaming and the associated changes in flow patterns and ice divides. We build on a recent inventory of Laurentide ice streams and use an existing ice margin chronology to produce the first detailed transient reconstruction of the ice stream drainage network in the LIS, which we depict in a series of palaeogeographic maps. Results show that the drainage network at the LGM was similar to modern-day Antarctica. The majority of the ice streams were marine terminating and topographically-controlled and many of these continued to function late into the deglaciation, until the ice sheet lost its marine margin. Ice streams with a terrestrial ice margin in the west and south were more transient and ice flow directions changed with the build-up, peak-phase and collapse of the Cordilleran-Laurentide ice saddle. The south-eastern marine margin in Atlantic Canada started to retreat relatively early and some of the ice streams in this region switched off at or shortly after the LGM. In contrast, the ice streams draining towards the north-western and north-eastern marine margins in the Beaufort Sea and in Baffin Bay appear to have remained stable throughout most of the Late Glacial, and some of them continued to function until after the Younger Dryas (YD). The YD influenced the dynamics of the deglaciation, but there remains uncertainty about the response of the ice sheet in several sectors. We tentatively ascribe the switching-on of some major ice streams during this period (e.g. M'Clintock Channel Ice Stream at the north-west margin), but for other large ice streams whose timing partially overlaps with the YD, the drivers are less clear and ice-dynamical processes, rather than effects of climate and surface mass balance are viewed as more likely drivers. Retreat rates markedly increased after the YD and the ice sheet became limited to the Canadian Shield. This hard-bed substrate brought a change in the character of ice streaming, which became less frequent but generated much broader terrestrial ice streams. The final collapse of the ice sheet saw a series of small ephemeral ice streams that resulted from the rapidly changing ice sheet geometry in and around Hudson Bay. Our reconstruction indicates that the LIS underwent a transition from a topographically-controlled ice drainage network at the LGM to an ice drainage network characterised by less frequent, broad ice streams during the later stages of deglaciation. These deglacial ice streams are mostly interpreted as a reaction to localised ice-dynamical forcing (flotation and calving of the ice front in glacial lakes and transgressing sea; basal de-coupling due to large amount of meltwater reaching the bed, debuttressing due to rapid changes in ice sheet geometry) rather than as conveyors of excess mass from the accumulation area of the ice sheet. At an ice sheet scale, the ice stream drainage network became less widespread and less efficient with the decreasing size of the deglaciating ice sheet, the final elimination of which was mostly driven by surface melt.

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https://doi.org/10.1016/j.quascirev.2018.03.013

1. Introduction

Ice streams have long been recognised for the Pleistocene ice sheets of the Northern Hemisphere (Løken and Hodgson, 1971; Hughes et al., 1977; Denton and Hughes, 1981; Dyke and Prest, 1987a; b; Dyke and Morris, 1988; Mathews, 1991; Patterson, 1998; Stokes and Clark, 2001; Ottesen et al., 2005; Kleman and Glasser, 2007; Winsborrow et al., 2012). Most attention has been given to the largest of these ice sheets, the Laurentide Ice Sheet (LIS), where some of the first investigations of palaeo-ice streams were undertaken (Løken and Hodgson, 1971; Dyke and Morris, 1988) and where an ice-discharge pattern broadly similar to the pattern of ice flow in modern ice sheets has gradually emerged (Dyke and Prest, 1987a; b; Patterson, 1998; De Angelis and Kleman, 2005; Stokes et al., 2009; Margold et al., 2015a; b).

A large number of ice streams have been identified for the LIS and ice streams are inferred to have operated during the build-up to the Last Glacial Maximum (LGM), at the LGM, and most commonly during its deglaciation (Denton and Hughes, 1981; Dyke and Prest, 1987a; b; Patterson, 1998; Stokes and Clark, 2003a; b; Winsborrow et al., 2004; De Angelis and Kleman, 2005, 2007; Stokes et al., 2009; Stokes and Tarasov, 2010; Stokes et al., 2012; Margold et al., 2015a; b). However, and perhaps surprisingly, ice streams have thus far not been fully included in any of the ice-sheet-wide reconstructions of the LIS evolution from the LGM to its disappearance in the Middle Holocene. We therefore have only a limited understanding of how the drainage network of ice streams and associated ice divides, domes and catchment areas interacted and evolved during deglaciation.

Denton and Hughes (1981) produced one of the first maps of putative ice stream locations and portrayed a topographically-controlled ice-stream network for the Canadian Arctic Archipelago (CAA) that, despite certain simplifications, largely resembled ice-drainage pattern shown in present-day reconstructions (De Angelis and Kleman, 2005; England et al., 2006; De Angelis and Kleman, 2007; Stokes et al., 2009; Margold et al., 2015 a; b). In contrast, the ice streams they depicted for the terrestrial portion of the ice sheet (terminating on land) were purely conceptual. Later reconstructions by Boulton et al. (1985) and Boulton and Clark (1990a, b) largely ignored ice streams, focussing instead on broader changes in flow geometry and ice divide configurations, and it was the reconstruction of Dyke and Prest (1987a, b) that first portrayed and discussed ice streams in more detail. Dyke and Prest (1987a, b) included some of the largest ice streams, most importantly the Hudson Strait Ice Stream, and they also recognised several of the smaller ice streams in the Canadian Arctic that are characterised by distinct sediment dispersal trains. However, their reconstruction lacked many of the ice streams on the continental shelf due to what is now known to be their overly restricted ice extent at the LGM (see review in Stokes, 2017). The 1990s saw a growing recognition that the southern lobes of the LIS represented terrestrial ice streams (Patterson, 1997, 1998). Subsequently, the development of objective criteria for palaeo-ice stream identification (Stokes and Clark, 1999, 2001), their application to the research of the LIS (see e.g., Clark and Stokes, 2001; De Angelis and Kleman, 2005; Kehew et al., 2005; Ross et al., 2006; Shaw et al., 2006), together with updated LGM ice extents on the continental shelf (England, 1999; Dyke et al., 2003; Dyke, 2004; England et al., 2006; Shaw et al., 2006), has resulted in a rapid increase in the number of ice streams that have been recognised (e.g., ~10 in Stokes and Clark, 2001; ~50 in Winsborrow et al., 2004; ~120 in Margold et al., 2015a, b).

Nevertheless, detailed reconstructions of ice streaming through time have thus far only been carried out for some specific sectors of the LIS, namely the south-western part of the CAA, Foxe Basin, the Hudson Strait region (De Angelis, 2007b; De Angelis and Kleman, 2007; Stokes et al., 2009) and the Atlantic seaboard south of Newfoundland (Shaw et al., 2006). Elsewhere, such as on the southern Interior Plains, ice streams have been studied but their evolution at the regional scale has not yet been fully constrained with the available chronological data (Evans et al., 1999; Evans et al., 2008; Ross et al., 2009; Ó Cofaigh et al., 2010; Evans et al., 2012, 2014). Furthermore, some regions of the LIS have largely escaped attention from an ice dynamical point of view; namely the central Interior Plains, the north-eastern coast of Labrador, and large parts of the LIS interior on the Canadian Shield (Margold et al., 2015a). The modelling of ice streams in the LIS has also seen some important advances (e.g. Sugden, 1977; MacAyeal, 1993; Marshall et al., 1996; Marshall and Clarke, 1997a; b; Kaplan et al., 2001; Calov et al., 2002; Stokes and Tarasov, 2010; Robel and Tziperman, 2016), but few studies have investigated the behaviour of ice streams throughout deglaciation. In addition to the complexity of the physics involved, a key limitation has been a lack of information on the location and timing of ice streams within the ice sheet that could either be compiled into an empirical reconstruction of ice streaming activity or used to test numerical modelling results (Stokes et al., 2015).

Here we build on and extend recent work on LIS ice streams. Margold et al. (2015b) produced an updated inventory of Laurentide ice streams based on a review of the literature and new mapping from across the ice sheet bed (reviewed in Margold et al., 2015a, Fig. 1). Using this inventory and the ice margin chronology of Dyke et al. (2003), Stokes et al. (2016a) recently bracketed the duration of each ice stream and calculated their likely discharge during deglaciation, guided by empirical data from modern ice streams. A key conclusion was that ice streaming was strongly scaled to the ice sheet volume and likely reduced in effectiveness during ice sheet deglaciation. Here, we extend that work by reconciling ice stream activity and the associated changes in ice stream catchments (and ice divides and domes) with the ice margin chronology (Dyke et al., 2003) into a palaeogeographic reconstruction of the LIS. We then discuss the reconstructed ice sheet evolution during the Late Glacial and early Holocene in the context of the available information on climate forcing and other possible drivers of ice stream activity.

2. Methods

2.1. Data

To reconstruct ice stream activity in the LIS we adopt the dating of ice stream operation presented by Stokes et al. (2016a), who used the recently-compiled inventory of Laurentide ice streams (Margold et al., 2015b) in combination with the North American ice retreat chronology of Dyke et al. (2003). The ice retreat chronology of Dyke et al. (2003), the construction of which is briefly described in Dyke (2004) and in the metadata of the 2003 Open File, builds on decades of earlier research (Prest et al., 1968; Bryson et al., 1969; Prest, 1969, 1970; Dyke and Prest, 1987a; b; Fulton, 1989) and combines the interpretation of the geomorphological and geological record (moraine systems, esker networks, drumlin orientation, regionally recognised tills, glaciolacustrine sediments) with a large set of ^{14}C ages, most of which are minimum deglaciation ages. This ice retreat chronology is the most up-to-date source of information for the entire ice sheet, but recent studies have shown that it significantly underestimates the ice extent on the continental shelf (e.g., England et al., 2006; Shaw et al., 2006; Rashid and Piper, 2007; England et al., 2009; Li et al., 2011; Batchelor et al., 2013a; b; 2014; Jakobsson et al., 2014; Brouard and Lajeunesse, 2017). Whilst there is now a consensus that grounded ice occupied large stretches of