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Advances in understanding subglacial meltwater drainage from past ice sheets

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Abstract

Meltwater drainage beneath ice sheets is a fundamental consideration for understanding ice–bed conditions and bed-modulated ice flow, with potential impacts on terminus behavior and ice-shelf mass balance. While contemporary observations reveal the presence of basal water movement in the subglacial environment and inferred styles of drainage, the geological record of former ice sheets, including sediments and landforms on land and the seafloor, aids in understanding the spatiotemporal evolution of efficient and inefficient drainage systems and their impact on ice-sheet behavior. We highlight the past decade of advances in geological studies that focus on providing process-based information on subglacial hydrology of ice sheets, how these studies inform theory, numerical models and contemporary observations, and address the needs for future research.

1. Introduction

Liquid water beneath ice sheets influences ice-flow organization and velocity (Kyrke-Smith and others, 2014; Bell and others, 2007; Larter and others, 2019), subglacial sediment rheology and transport (Damsgaard and others, 2020; Minchew and Meyer, 2020), grounding-line behavior (Horgan and others, 2013; Fried and others, 2015) and ice-shelf mass balance (Le Brocq and others, 2013; Alley and others, 2016). Ice-sheet response, however, is contingent on subglacial water supply and drainage organization (Röthlisberger, 1972; Walder, 1986; Schoof, 2010). While some components of subglacial hydrological systems are relatively stable (i.e. fixed), such as large subglacial lakes beneath the East Antarctic ice sheet (Kapitsa and others, 1996) and incised bedrock channels (Kirkham and others, 2020), other reservoirs and drainage pathways are more transient and evolve through time and space with non-linear and spatially heterogeneous impacts on ice-sheet behavior (Schroeder and others, 2013; Andrews and others, 2014; Hoffman and others, 2016; Siegfried and others, 2016; Rada and Schoof, 2018). Beyond the grounding line, contemporary sediment plumes emanating from marine-terminating outlet glaciers of the Greenland ice sheet observed via satellite imagery (Fried and others, 2015; Schild and others, 2016) and surficial expressions of channelization beneath Antarctic ice shelves (Le Brocq and others, 2013; Alley and others, 2016) indicate active subglacial hydrological systems upstream.

Major advances in observing contemporary ice-sheet hydrology, such as radar specularity (Schroeder and others, 2013) and repeat satellite measurements (Fricker and others, 2016), reveal spatiotemporal evolution of basal water transmission on sub-decadal scales. Yet, the limited nature of long-term (decadal to millennial) observations impedes holistic perspectives on the modes and magnitudes of water drainage beneath ice sheets and their consequences for ice-sheet behavior. In formerly glaciated landscapes and continental margins, relict subglacial water drainage is recorded by meltwater landforms and sedimentological successions (Fig. 1; Kehew and others, 2012; Lee and others, 2015; Greenwood and others, 2016; Esteves and others, 2017). Channels (broadly defined) incised into bedrock and sediments and positive-relief esker ridges record drainage styles and organization (Storrar and others, 2014; Zoet and others, 2019; Lewington and others, 2020) and, in some cases, associated ice-margin retreat behavior (Livingstone and others, 2020; Simkins and others, 2021) and creation of tidal embayments in grounding lines (Horgan and others, 2013). Distinct meltwater plume deposits and hydrologically sorted sediments reveal relative magnitudes and frequency of water drainage into the ocean, precursory, synchronous or resulting glacial environment changes, and geochemical signatures of sediment and water provenance (Witus and others, 2014; O'Regan and others, 2021; Lepp and others, 2022). Such empirical observations based on the geological record have long guided and continue to inform, and challenge, glaciological theory (e.g. Walder and Hallet, 1979; Boulton and others, 2009; Hewitt, 2011).

2. Recent scientific advances from paleo-ice sheets

Over the past decade, advances in geophysical methods, growing data accessibility and sedimentological studies from deglaciated terrains have pushed the boundaries of subglacial

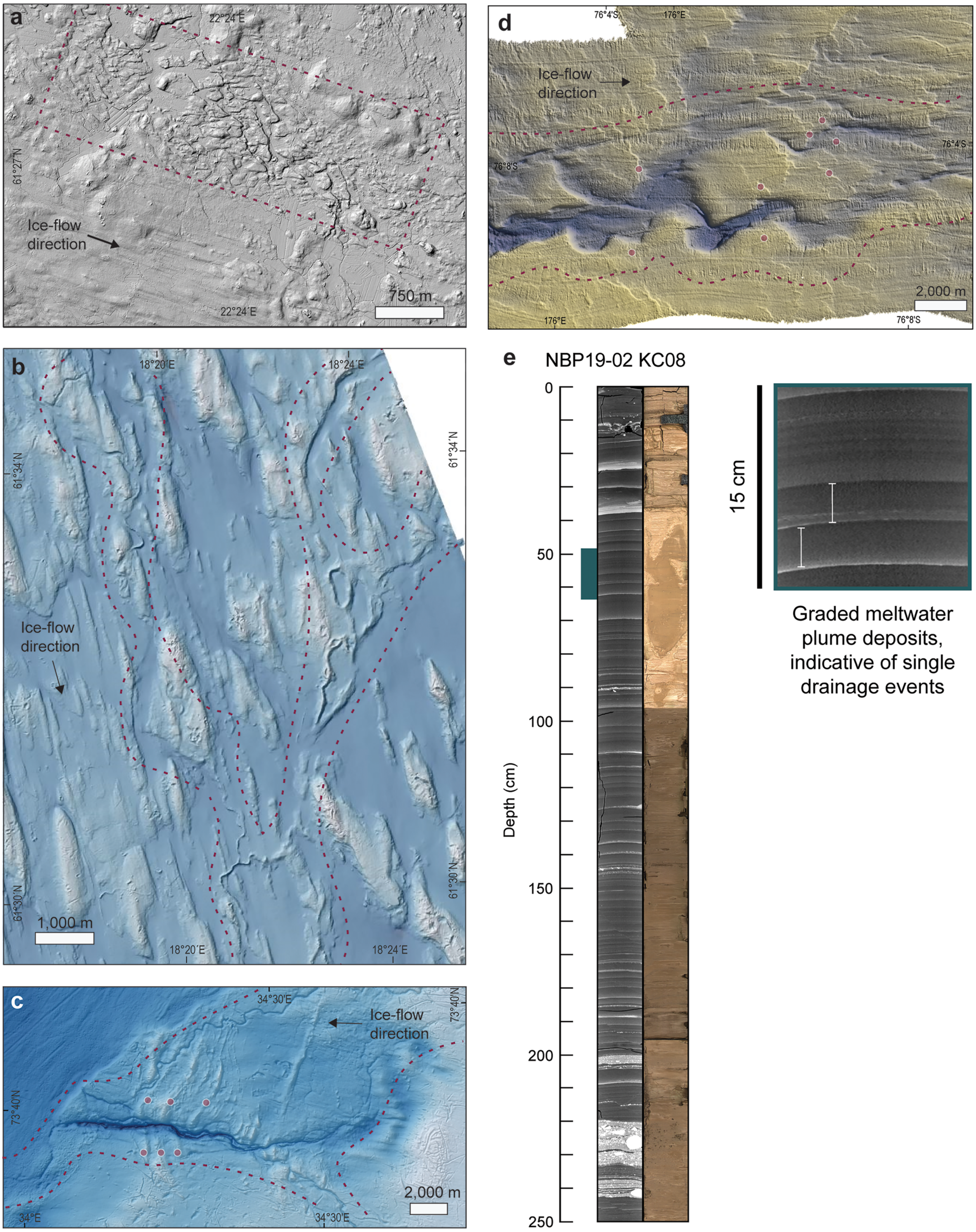

Fig. 1. (a) Murtoo pathway within glacially streamlined terrain in central Finland (Mäkinen and others, 2017; Ojala and others, 2019). Data: LiDAR-based DEM from the National Land Survey of Finland. (b) Meltwater channels and eskers drape and incise drumlins in the Bothnian Sea (Greenwood and others, 2017). Data: MBES-based DEM from the Swedish Maritime Administration. (c) Meltwater channel incised retreat moraines (red dots) on Thor Iversenbanken in the Central Barents Sea (Esteves and others, 2017). Data: MAREANO MBES-based bathymetry from the Norwegian Mapping Authority. (d) Meltwater corridor in which channels cross-cut grounding zone wedges (red dots) in the Ross Sea, Antarctica (Simkins and others, 2021). Data: MBES-based DEM from cruise NBP15-02, available through the United States Antarctic Program Data Center. In (a)–(d), red dashed lines outline the encompassing areas of meltwater landforms. (e) CT scan and photograph of the upper 250 cm of sediment core NBP19-02 KC-08, collected in the Amundsen Sea, records meltwater plume events that emanated from the Thwaites Glacier grounding line (Lepp and others, 2022).

hydrology understanding and challenged concepts of the spatio-temporal evolution of water drainage beneath ice sheets. Near complete coverage of light detection and ranging (LiDAR) and satellite photogrammetry elevation data across terrestrial landscapes formerly glaciated by the European and North American ice sheets, give unprecedented views of paleo-subglacial meltwater landforms that range in relief from 10^{-1} to 10^{2} m and lengths of 10^{1}–10^{5} m, allowing holistic ice-sheet scale assessment of controls on drainage. While nowhere near as complete, increasing coverage and quality of bathymetry data from deglaciated continental shelves provide perspectives on water flow beneath marine-based ice sheets and implications for ice-sheet behavior at fine scales previously unseen. These offshore advances via multibeam echo sounding (MBES) surveys are facilitated by national hydrographic programs such as MAREANO (e.g. Esteves and others, 2017), marine geological repositories such as the Marine Geoscience Data System and researcher-led surveying and compilations (e.g. Greenwood and others, 2021). Additionally, 3-D seismic survey grids, albeit sparse but increasing in spatial coverage due to industry-academic relations, are unique datasets to assess temporal evolution of drainage pathways and internal architecture of meltwater landforms (e.g. Kirkham and others, 2021, 2022). These advances in terrain data acquisition and availability have not only permitted ice-sheet scale documentation of small-scale (meter to sub-meter) and intricate meltwater landforms, demonstrating their variability as well as near ubiquity, but have also uncovered both new types of landforms and little recognized meltwater landform assemblages, stimulating new hypotheses for meltwater landform genesis and understanding of the coupling to ice-flow and ice-margin behavior (Storrar and others, 2014; Ojala and others, 2019; Kirkham and others, 2020).

Challenging the traditional binary categorization of subglacial drainage through either ‘channelized’ or ‘distributed’ pathways (Röthlisberger, 1972; Kamb, 1987), meltwater corridors found in the Northern Hemisphere (e.g. Peterson and others, 2018; Lewington and others, 2020), and on the Antarctic seafloor (Simkins and others, 2021) represent broad subglacial drainage pathways of meltwater landform assemblages that span 10^{1}–10^{2} km in length. Corridor-like drainage systems have also been identified beneath the contemporary Greenland ice sheet (Hoffman and others, 2016; Davison and others, 2019) with complex configurations evolving depending on hydraulic gradients, meltwater input to the subglacial environment and sediment deformation (Davison and others, 2019). These corridors indicate co-existence of drainage styles, varying genetic erosional and depositional processes and waxing and waning of drainage magnitudes in time and space. Additionally, newly observed landforms in Scandinavia, termed murtoos, potentially bridge the long-standing gap in recognizing geomorphic evidence for distributed subglacial drainage (Mäkinen and others, 2017; Ojala and others, 2019). These low-relief triangular subglacial landforms oriented with their apex in the ice-flow direction (Fig. 1a) often occur with other meltwater landforms such as channels and eskers, and sediments which have undergone hydraulic sorting, ductile deformation and liquefaction (Becher and Johnson, 2021). Collectively, murtoo presence suggests efficient transitional drainage between channelized and distributed under high-pressure conditions, potentially in response to transient linked cavity-type drainage systems (Ojala and others, 2022) similar to those beneath the Greenland ice sheet (Hoffman and others, 2016). Both corridors and murtoos point to variable modes of drainage that co-exist or evolve in time and space including ‘efficient’ and ‘inefficient’ components, thus questioning the validity of assuming or parameterizing singular modes of subglacial water drainage.

A long-standing challenge in glacial geomorphology has been how to interpret the temporal significance of meltwater landforms: the time required, and the stability of discharge required, for both landform and whole drainage pathway formation. Meltwater landform relations to other subglacial and ice-marginal landforms provide insights in this regard (e.g. Greenwood and others, 2017; Simkins and others, 2017; Ojala and others, 2019; Livingstone and others, 2020). For example, drumlins and mega-scale glacial lineations incised by channels and draped by eskers in the Bothnian Sea indicate a geomorphic switch from active bedform shaping to channelized water drainage overprinting stable bedforms, shortly before deglaciation (Fig. 1b; Greenwood and others, 2017). Here, interlinking channels and eskers of comparable sizes within a coherent drainage path highlight the transitory dominance of erosion and deposition in the subglacial environment. Episodic esker segment (‘bead’) deposition has long been inferred from the terrestrial landform-sediment record (De Geer, 1897; Banerjee and McDonald, 1975; Mäkinen, 2003). Livingstone and others (2020) demonstrate a tight relationship between esker beads and De Geer moraines in central Nunavut and infer time-transgressive landform building by drainage pathways to the ice margin. Similarly, meltwater channel incision through retreat moraines in the Barents Sea (Fig. 1c; Esteves and others, 2017) and variable incision of or draping by retreat moraines in the western Ross Sea (Simkins and others, 2017) indicate the relative persistence of channelized drainage during active ice-margin retreat. Embayments can form where meltwater channels drain at grounding lines (Horgan and others, 2013; Simkins and others, 2017) likely through grounding-line sediment non-deposition, with potential to enhance tidal action at and upstream of the grounding line as ocean water flushes in and out of the channel path as observed at the contemporary Whillans Ice Stream (Horgan and others, 2013). A corridor of over 80 meltwater channels on the Antarctic continental shelf (Fig. 1d; Simkins and others, 2021) had prolonged impacts on grounding-line behavior as larger magnitude grounding-line retreat events and grounding zone wedge deposition occurred while the channels within the corridor were active, compared to smaller retreat events and moraine deposition when the channels were inactive. While the mechanism for this relationship remains unknown, it possibly results from hydrological controls on sediment rheology and mobility that influence building of ice-marginal landforms that may or may not reduce effective water depths enough to counterbalance grounding-line buoyancy-driven retreat. Such observations of meltwater–grounding-line landform associations and the potential to document these over large tracts of paleo-ice-sheet beds offer new possibilities for constraining the time component of the meltwater landform record, as well as quantifying sediment loads and, for example, seasonal deposition of individual esker beads.

Complementary to geomorphological studies, sediment records from deglaciated continental shelves and proglacial lake basins elucidate the temporal persistence of subglacial and grounding-line water discharge and associated changes in ice-sheet configuration and behavior (e.g. Rüther and others, 2012; Lee and others, 2015; Avery and others, 2021; O'Regan and others, 2021; Lepp and others, 2022). Meltwater plume deposits offshore of Thwaites Glacier, Antarctica and Ryder Glacier, Greenland are a common feature associated with (or precursor to) glacier retreat and ice-shelf break up events, indicated by the millimeter-scale stratigraphy resolved by computed tomography (CT) scans and by grain-scale sedimentology (Fig. 1e; O'Regan and others, 2021; Lepp and others, 2022). Downcore stratigraphy and trace elemental ratios in cores that sample meltwater plume deposits reveal differences in relative magnitudes and frequencies of subglacial drainage into the ocean offshore of western and eastern Thwaites Glacier, and suggest greater magnitudes of sediment-laden water were delivered to the ocean in recent

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centuries compared to the past several thousand years (Lepp and others, 2022). In the Baltic Sea basin, where proglacial varved sediments have long been used to document the pattern and pace of Fennoscandian ice-margin retreat, Avery and others (2021) find multi-decadal cycles of enhanced meltwater discharge through a 725 year varve series, ~15 000 years ago. In these paleo cases, and particularly where the former ice-sheet bed is now exposed, there is great potential for examining links between the temporal information archived in the distal sedimentological record of meltwater events and longevity of discharge, and the high-resolution geomorphology of the hydrological system responsible.

A recent body of work examining physical processes of and conditions for subglacial fluvial erosion, deposition and sediment mobility is an important step forward (Beaud and others, 2016, 2018; Damsgaard and others, 2017; Hewitt and Creyts, 2019; Kirkham and others, 2022; Stevens and others, 2022; Vérité and others, 2022). These studies build towards an integrated or continuum view of meltwater organization, depending on water supply and sources, basal conditions and substrate properties. Importantly, they make advances towards knowledge of where, over what timescales, and with what meltwater discharge regimes, sediments are mobilized and landforms may form, opening up the vast landform record to much more effective and accurate use as a document of coupled meltwater – ice flow – ice margin behavior in paleo-ice sheets over seasonal-to-millennial timescales.

3. Looking forward

To push the field of subglacial hydrology forward using the landform and sediment records of deglaciated regions, we need: increased geophysical data coverage in regions proximal to contemporary ice-sheet margins; coupled remote-sensing and field-based observations in terrestrial landscapes; reporting of quantitative sedimentologic and morphometric data and community building to work across disciplinary bounds and study-area silos. Of promise in narrowing knowledge gaps are emerging themes of research on deeper groundwater interactions with the ice–bed interface (Gustafson and others, 2022) and its implications for landform genesis (Boulton and others, 2009; Hermanowski and Piotrowski, 2019), understanding subglacial lake and ice-sheet surface connections to subglacial drainage systems (Greenwood and others, 2016; Simkins and others, 2017), assessment of the role of local (10^0–10^1 m relief) variability in bed conditions on drainage organization (Simkins and others, 2021) and the continued pursuit of constraining time for meltwater landform construction and evolution; each of these pursuits will benefit from more seamless integration of theory, numerical models and coupled geomorphological and chronological studies (Kirkham and others, 2022; Stevens and others, 2022). Additionally, higher-resolution topographic data from the surface of Mars offer opportunities to dig deeper into the surficial expressions of meltwater landforms (e.g. Butcher and others, 2020), whereby comparison with Earth's meltwater landforms may offer new insights into key processes controlling their genesis. Here on Earth and on Mars, we need to be mindful of what we are not seeing, such as evidence for distributed, transient and hard-bed systems that might not leave their mark, in geomorphological and sedimentological records of subglacial hydrological systems. Additionally, when planning new research projects, those of us working on records of paleo-ice sheets and those studying contemporary ice sheets should draw on literature from the two respective fields to identify key gaps in understanding of subglacial hydrological forms and processes that will aid in assessing the future of the Greenland and Antarctic ice sheets.

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