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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, including sediments and landforms, on land and the seafloor of former or formerly expanded ice sheets aid in understanding the spatiotemporal evolution of distributed and channelized 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 (Bell et al., 2007; Kyrke-Smith et al., 2014; Larter et al., 2019), subglacial sediment rheology and transport (Damsgaard et al., 2020; Minchew & Meyer, 2020), grounding-line behavior (Horgan et al., 2013; Fried et al., 2015), and ice-shelf mass balance (Le Brocq et al., 2013; Alley et al., 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 et al., 1996) and incised bedrock channels (Kirkham et al., 2020), other reservoirs and drainage pathways are more transient and evolve through time and space with nonlinear and spatially heterogeneous impacts on ice-sheet behavior (Schroeder et al., 2013; Andrews et al., 2014; Hoffman et al., 2016; Siegfried et al., 2016; Rada & 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 et al., 2015; Schild et al., 2016) and surficial expressions of channelization beneath Antarctic ice shelves (Le Brocq et al., 2013; Alley et al., 2016) indicate active subglacial hydrological systems upstream.

Major advances in observing contemporary ice-sheet hydrology, such as radar specularity (Schroeder et al., 2013) and repeat satellite measurements (Fricker et al., 2015), reveal spatiotemporal evolution of basal water transmission on sub-decadal scales. Yet, limited long-term (decadal to millennial) observations impede 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 et al., 2012; Lee et al., 2015; Esteves et al., 2017; Greenwood et al., 2016).

Channels (broadly defined) incised into bedrock and sediments and positive-relief esker ridges record drainage styles and organization (Storrar et al., 2014; Zoet et al., 2018; Lewington et al., 2020) and, in some cases, associated ice-margin retreat behavior (Livingstone et al., 2020; Simkins et al., 2021). 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 et al., 2014; O'Regan et al., 2021; Lepp et al., 2022). Such empirical observations based on the geological record have long guided and continue to inform, and challenge, glaciological theory (e.g., Walder & Hallet 1979; Boulton et al. 2009; Hewitt, 2011).

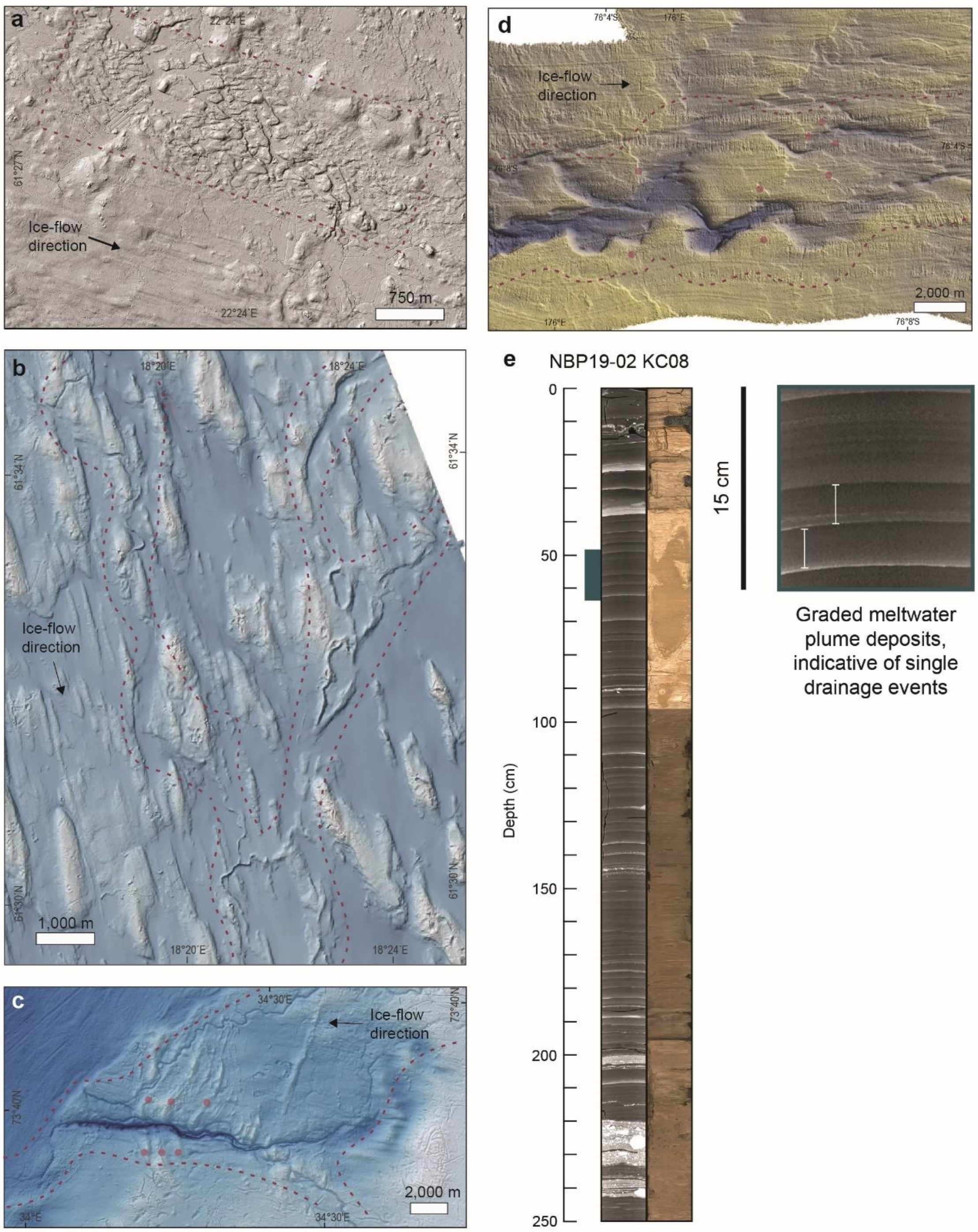

Fig. 1. (a) Murtoo pathway within glacially streamlined terrain in central Finland (Mäkinen et al. 2017; Ojala et al. 2019). Data: LiDAR-based DEM from the National Land Survey of Finland. (b) Meltwater channels and eskers drape and incise drumlins in the Bothnian Sea (Greenwood et al. 2017). Data: MBES-based DEM from the Swedish Maritime Administration. (c) Meltwater channel incised retreat moraines (red dots) on Thor Iversenbanken in the Central Barents Sea (Esteves et al., 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 et al. 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) Computed tomography (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 et al. 2022).

2. Recent advances from paleo-ice sheets

Over the past decade, advances in geophysical methods, growing data accessibility, and sedimentological studies from deglaciated terrains push the boundaries of subglacial hydrology understanding and challenge concepts of the spatiotemporal 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, gives unprecedented views of paleo-subglacial meltwater landforms that range in relief from 10^{-1} to 10^{2} of meters and lengths of 10^{1} to 10^{5} meters, 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 provides 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 et al., 2017), marine geological repositories such as the Marine Geoscience Data System, and researcher-led surveying and compilations (e.g., Greenwood et al., 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 et al., 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 et al., 2014; Ojala et al., 2019; Kirkham et al., 2020).

Challenging the binary categorization of subglacial drainage through either “channelized” or “distributed” pathways, meltwater corridors found in the Northern Hemisphere (e.g., Peterson et al., 2018; Lewington et al., 2020), and on the Antarctic seafloor (Simkins et al., 2021) represent broad subglacial drainage pathways of meltwater landform assemblages that span 10^{1}-10^{2} kilometers in length. 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 et al. 2017; Ojala et al., 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 & 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 et al., 2022) similar to those beneath the Greenland Ice Sheet (Hoffman et al., 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., Simkins et al., 2017; Greenwood et al., 2017; Ojala et al., 2019; Livingstone et al., 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 et al., 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 et al. (2020) demonstrate a tight relationship between esker beads and De Geer moraines in central Nunavut and infer time-transgressive landform building, yet relatively fixed in space, by drainage pathways to the ice margin. Similarly, meltwater channel incision through retreat moraines in the Barents Sea (Fig. 1c; Esteves et al., 2017) and variable incision of or draping by retreat moraines in the western Ross Sea (Simkins et al. 2017) indicate the relative persistence of channelized drainage during active ice-margin retreat. A corridor of over 80 meltwater channels on the Antarctic continental shelf (Fig. 1d; Simkins et al., 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. Such observations of meltwater - grounding line landform associations and the potential to document these over large tracts of paleo-ice sheet beds offers 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 et al., 2012; Lee et al., 2015; Avery et al., 2021; O’Regan et al., 2021; Lepp et al., 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 et al., 2021; Lepp et al., 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 centuries compared to the past several thousand years (Lepp et al., 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 et al. (2021) find multi-decadal cycles of enhanced meltwater discharge through a 725-year varve series, around 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 et al., 2016, 2018; Damsgaard et al., 2017; Hewitt and Creyts, 2019; Kirkham et al., 2022; Vérité et al., 2022; Stevens et al., 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 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 et al., 2022) and its implications for landform genesis (Boulton et al., 2009; Hermanowski and Piotrowski, 2019), understanding subglacial lake and ice-sheet surface connections to subglacial drainage systems (Greenwood et al., 2016; Simkins et al., 2017), assessment of the role of local (10^0-10^1 m relief) variability in bed conditions on drainage organization (Simkins et al., 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 et al., 2022; Stevens et al., 2022). Additionally, higher-resolution topographic data from the surface of Mars offers opportunities to dig deeper into the surficial expressions of meltwater landforms (e.g., Butcher et al., 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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References

Alley, K. E., Scambos, T. A., Siegfried, M. R., & Fricker, H. A. (2016). Impacts of warm water on Antarctic ice shelf stability through basal channel formation. Nat. Geosci., 9(4), 290-293.

Andrews, L. C., Catania, G. A., Hoffman, M. J., Gulley, J. D., Lüthi, M. P., Ryser, C., & Neumann, T. A. (2014). Direct observations of evolving subglacial drainage beneath the Greenland Ice Sheet. Nature, 514(7520), 80–83.

Avery, R. S., Greenwood, S. L., Schenk, F., Morén, B. M., Armstrong Mckay, D. I., Brunnberg, L., & Wohlfarth, B. (2021). A 725-year integrated offshore terrestrial varve chronology for southeastern Sweden suggests rapid ice retreat~ 15 ka BP. Boreas, 50(2), 477-496.

Banerjee, I. and McDonald, B.C (1975). Nature of esker sedimentation, in Glaciofluvial and glaciolacustrine sedimentation, Jopling, A. V., & McDonald, B. C. (Eds.). SEPM Sp. Pub. 23, 132–154.

Beaud, F., Flowers, G. E., & Venditti, J. G. (2016). Efficacy of bedrock erosion by subglacial water flow. Earth Surf. Dyn., 4(1), 125-145.

Beaud, F., Flowers, G. E., & Venditti, J. G. (2018). Modeling sediment transport in ice-walled subglacial channels and its implications for esker formation and proglacial sediment yields. J.Geophys. Res.: Earth Surf., 123(12), 3206-3227.

Bell, R. E., Banwell, A. F., Trusel, L. D., & Kingslake, J. (2018). Antarctic surface hydrology and impacts on ice-sheet mass balance. Nat. Clim. Chan., 8(12), 1044-1052.

Boulton, G.S., Hagdorn, M., Maillot, P.B. & Zatsepin, S. 2009. Drainage beneath ice sheets: groundwater–channel coupling, and the origin of esker systems from former ice sheets. Quat. Sci. Rev. 28, 621–638.

Butcher, F. E., Balme, M. R., Conway, S. J., Gallagher, C., Arnold, N. S., Storrar, R. D., ... & Hagermann, A. (2020). Morphometry of a glacier-linked esker in NW Tempe Terra, Mars, and implications for sediment-discharge dynamics of subglacial drainage. Earth and Planet. Sci. Lett., 542, 116325.

Damsgaard, A., Suckale, J., Piotrowski, J. A., Houssais, M., Siegfried, M. R., & Fricker, H. A. (2017). Sediment behavior controls equilibrium width of subglacial channels. J. Glaciology, 63(242), 1034-1048.

Damsgaard, A., Goren, L., & Suckale, J. (2020). Water pressure fluctuations control variability in sediment flux and slip dynamics beneath glaciers and ice streams. Comm. Earth & Enviro., 1(1), 1-8.

De Geer, G. (1897) Om rullstensåsarnas bildningssätt. GFF, 19(5), 366-388.

Esteves, M., Bjarnadóttir, L. R., Winsborrow, M. C., Shackleton, C. S., & Andreassen, K. (2017). Retreat patterns and dynamics of the Sentralbankrenna glacial system, central Barents Sea. Quaternary Science Reviews, 169, 131-147.

Fricker, H. A., Siegfried, M. R., Carter, S. P., & Scambos, T. A. (2016). A decade of progress in observing and modelling Antarctic subglacial water systems. Phil.Trans. R. Soc. A: Math., Phy. Eng. Sci., 374(2059), 20140294.

Fried, M. J., Catania, G. A., Bartholomaus, T. C., Duncan, D., Davis, M., Stearns, L. A., ... & Sutherland, D. (2015). Distributed subglacial discharge drives significant submarine melt at a Greenland tidewater glacier. Geophys. Res. Lett., 42(21), 9328-9336.

Greenwood, S. L., Clason, C. C., Helanow, C., & Margold, M. (2016). Theoretical, contemporary observational and palaeo-perspectives on ice sheet hydrology: processes and products. Ear.-Sci. Rev., 155, 1-27.

Greenwood, S. L., Clason, C. C., Nyberg, J., Jakobsson, M., & Holmlund, P. (2017). The Bothnian Sea ice stream: early Holocene retreat dynamics of the south-central Fennoscandian Ice Sheet. Boreas, 46(2), 346-362.

Greenwood, S. L., Simkins, L. M., Winsborrow, M. C., & Bjarnadóttir, L. R. (2021). Exceptions to bed-controlled ice sheet flow and retreat from glaciated continental margins worldwide. Sci. Adv., 7(3), eabb6291.

Gustafson, C. D., Key, K., Siegfried, M. R., Winberry, J. P., Fricker, H. A., Venturelli, R. A., & Michaud, A. B. (2022). A dynamic saline groundwater system mapped beneath an Antarctic ice stream. Science, 376(6593), 640-644.

Hermanowski, P. & Piotrowski, J.A. (2019). Groundwater flow under a paleo-ice stream of the Scandinavian Ice Sheet and its implications for the formation of Stargard drumlin field, NW Poland. J.Geophys. Res.: Earth Surf., 124(7), 1720-1741.

Hewitt, I. 2011. Modelling distributed and channelized subglacial drainage: The spacing of channels. J. Glaciol. 57, 302-314.

Hewitt, I. J., & Creyts, T. T. (2019). A model for the formation of eskers. Geophys. Res. Lett., 46(12), 6673-6680.

Hoffman, M. J., Andrews, L. C., Price, S. F., Catania, G. A., Neumann, T. A., Lüthi, M. P., & Morriss, B. (2016). Greenland subglacial drainage evolution regulated by weakly connected regions of the bed. Nat. Comm., 7(1), 1–12.

Horgan, H. J., Alley, R. B., Christianson, K., Jacobel, R. W., Anandakrishnan, S., Muto, A., ... & Siegfried, M. R. (2013). Estuaries beneath ice sheets. Geology, 41(11), 1159-1162.

Kapitsa, A. P., Ridley, J. K., de Q Robin, G., Siegert, M. J., & Zotikov, I. A. (1996). A large deep freshwater lake beneath the ice of central East Antarctica. Nature, 381(6584), 684-686.

Kehew, A. E., Piotrowski, J. A., & Jørgensen, F. (2012). Tunnel valleys: Concepts and controversies—A review. Ear.-Sci. Rev., 113(1-2), 33-58.

Kirkham, J. D., Hogan, K. A., Larter, R. D., Arnold, N. S., Nitsche, F. O., Kuhn, G., ... & Dowdeswell, J. A. (2020). Morphometry of bedrock meltwater channels on Antarctic inner continental shelves: Implications for channel development and subglacial hydrology. Geomorph., 370, 107369.

Kirkham, J. D., Hogan, K. A., Larter, R. D., Self, E., Games, K., Huuse, M., ... & Dowdeswell, J. A. (2021). Tunnel valley infill and genesis revealed by high-resolution 3-D seismic data. Geology, 49(12), 1516-1520.

Kirkham, J. D., Hogan, K. A., Larter, R. D., Arnold, N. S., Ely, J. C., Clark, C. D., ... & Dowdeswell, J. A. (2022). Tunnel valley formation beneath deglaciating mid-latitude ice sheets: Observations and modelling. Quat. Sci. Rev., 107680.

Kyrke-Smith, T. M., Katz, R. F., & Fowler, A. C. (2014). Subglacial hydrology and the formation of ice streams. Proc. R. Soc. A: Math. Phys. Eng. Sci., 470(2161), 20130494.

Larter, R. D., Hogan, K. A., Hillenbrand, C. D., Smith, J. A., Batchelor, C. L., Cartigny, M., ... & Dowdeswell, J. A. (2019). Subglacial hydrological control on flow of an Antarctic Peninsula palaeo-ice stream. Cryosphere, 13(6), 1583-1596.

Le Brocq, A. M., Ross, N., Griggs, J. A., Bingham, R. G., Corr, H. F., Ferraccioli, F., ... & Siegert, M. J. (2013). Evidence from ice shelves for channelized meltwater flow beneath the Antarctic Ice Sheet. Nat. Geosci., 6(11), 945-948.

Lee, J. R., Wakefield, O. J., Phillips, E., & Hughes, L. (2015). Sedimentary and structural evolution of a relict subglacial to subaerial drainage system and its hydrogeological implications: an example from Anglesey, north Wales, UK. Quat. Sci. Rev. 109, 88-110.

Lepp, A. P., Simkins, L. M., Anderson, J. B., Clark, R. W., Wellner, J. S., Hillenbrand, C. D., ... & Wacker, L. (2022). Sedimentary Signatures of Persistent Subglacial Meltwater Drainage From Thwaites Glacier, Antarctica. Fron. Earth Sci., 10.

Lewington, E. L., Livingstone, S. J., Clark, C. D., Sole, A. J., & Storrar, R. D. (2020). A model for interaction between conduits and surrounding hydraulically connected distributed drainage based on geomorphological evidence from Keewatin, Canada. Cryosphere, 14(9), 2949-2976.

Livingstone, S. J., Lewington, E. L., Clark, C. D., Storrar, R. D., Sole, A. J., McMartin, I., ... & Ng, F. (2020). A quasi-annual record of time-transgressive esker formation: Implications for ice-sheet reconstruction and subglacial hydrology. Cryosphere, 14(6), 1989-2004.

Mäkinen, J. (2003). Time-transgressive deposits of repeated depositional sequences within interlobate glaciofluvial (esker) sediments in Köyliö, SW Finland. Sedimentology, 50(2), 327-360.

Mäkinen, J., Kajuutti, K., Palmu, J. P., Ojala, A., & Ahokangas, E. (2017). Triangular-shaped landforms reveal subglacial drainage routes in SW Finland. Quat. Sci. Rev., 164, 37-53.

Minchew, B. M., & Meyer, C. R. (2020). Dilation of subglacial sediment governs incipient surge motion in glaciers with deformable beds. Proc. R. Soc. A, 476(2238), 20200033.

Ojala, A. E., Peterson, G., Mäkinen, J., Johnson, M. D., Kajuutti, K., Palmu, J. P., ... & Öhrling, C. (2019). Ice-sheet scale distribution and morphometry of triangular-shaped hummocks (murtoos): a subglacial landform produced during rapid retreat of the Scandinavian Ice Sheet. A. Glaciol., 60(80), 115-126.

Ojala, A. E., Mäkinen, J., Kajuutti, K., Ahokangas, E., & Palmu, J. P. (2022). Subglacial evolution from distributed to channelized drainage: Evidence from the Lake Murtoo area in SW Finland. Earth Surf. Proc. Land., 47(12), 2877-2896.

O'Regan, M., Cronin, T. M., Reilly, B., Alstrup, A. K. O., Gemery, L., Golub, A., ... & Jakobsson, M. (2021). The Holocene dynamics of Ryder Glacier and ice tongue in north Greenland. Cryosphere, 15(8), 4073-4097.

Peterson, G., Johnson, M. D., Dahlgren, S., Påsse, T., & Alexanderson, H. (2018). Genesis of hummocks found in tunnel valleys: an example from Hörda, southern Sweden. GFF, 140(2), 189-201.

Becher, G. P., & Johnson, M. D. (2021). Sedimentology and internal structure of murtoos-V-shaped landforms indicative of a dynamic subglacial hydrological system. Geomorph., 380, 107644.

Rada, C., & Schoof, C. (2018). Channelized, distributed, and disconnected: subglacial drainage under a valley glacier in the Yukon. Cryosphere, 12(8), 2609-2636.

Röthlisberger, H. (1972). Water Pressure in Intra- and Subglacial Channels. J. Glaciol., 11(62), 177–203.

Rüther, D. C., Bjarnadóttir, L. R., Junttila, J., Husum, K., Rasmussen, T. L., Lucchi, R. G., & Andreassen, K. (2012). Pattern and timing of the northwestern Barents Sea Ice Sheet deglaciation and indications of episodic Holocene deposition. Boreas, 41(3), 494-512.

Schild, K. M., Hawley, R. L., & Morriss, B. F. (2016). Subglacial hydrology at Rink Isbræ, West Greenland inferred from sediment plume appearance. A. Glaciol., 57(72), 118-127.

Schoof, C. (2010). Ice-sheet acceleration driven by melt supply variability. Nature, 468(7325), 803–806.

Schroeder, D. M., Blankenship, D. D., & Young, D. A. (2013). Evidence for a water system transition beneath Thwaites Glacier, West Antarctica. Proc. Nat. Acad. Sci., 110(30), 12225–12228.

Siegfried, M. R., Fricker, H. A., Carter, S. P., & Tulaczyk, S. (2016). Episodic ice velocity fluctuations triggered by a subglacial flood in West Antarctica. Geophys. Res. Lett., 43(6), 2640-2648.

Simkins, L. M., Anderson, J. B., Greenwood, S. L., Gonnermann, H. M., Prothro, L. O., Halberstadt, A. R. W., ... & DeConto, R. M. (2017). Anatomy of a meltwater drainage system beneath the ancestral East Antarctic ice sheet. Nat. Geosci., 10(9), 691-697.

Simkins, L. M., Greenwood, S. L., Munevar Garcia, S., Eareckson, E. A., Anderson, J. B., & Prothro, L. O. (2021). Topographic controls on channelized meltwater in the subglacial environment. Geophys. Res. Lett., 48(20), e2021GL094678.

Stevens, D., Ely, J. C., Livingstone, S. J., Clark, C. D., Butcher, F. E., & Hewitt, I. (2022). Effects of basal topography and ice-sheet surface slope in a subglacial glaciofluvial deposition model. J. Glaciol., 1-13.

Storrar, R. D., Stokes, C. R., & Evans, D. J. (2014). Morphometry and pattern of a large sample (> 20,000) of Canadian eskers and implications for subglacial drainage beneath ice sheets. Quat. Sci. Rev., 105, 1-25.

Vérité, J., Ravier, É., Bourgeois, O., Bessin, P., Livingstone, S. J., Clark, C. D., ... & Mourgues, R. (2022). Formation of murtoos by repeated flooding of ribbed bedforms along subglacial meltwater corridors. Geomorphol., 408, 108248.

Walder, J. S. (1986). Hydraulics of Subglacial Cavities. J. Glaciol., 32(112), 439–445.

Walder, J. & Hallet, B. 1979. Geometry of former subglacial water channels and cavities. J. Glaciol. 23, 335-346.

Witus, A. E., Branecky, C. M., Anderson, J. B., Szczuciński, W., Schroeder, D. M., Blankenship, D. D., & Jakobsson, M. (2014). Meltwater intensive glacial retreat in polar environments and investigation of associated sediments: example from Pine Island Bay, West Antarctica. Quat. Sci. Rev., 85, 99-118.

Zoet, L. K., Muto, A., Rawling III, J. E., & Attig, J. W. (2019). The effects of tunnel channel formation on the Green Bay lobe, Wisconsin, USA. Geomorph., *324*, 36-47.

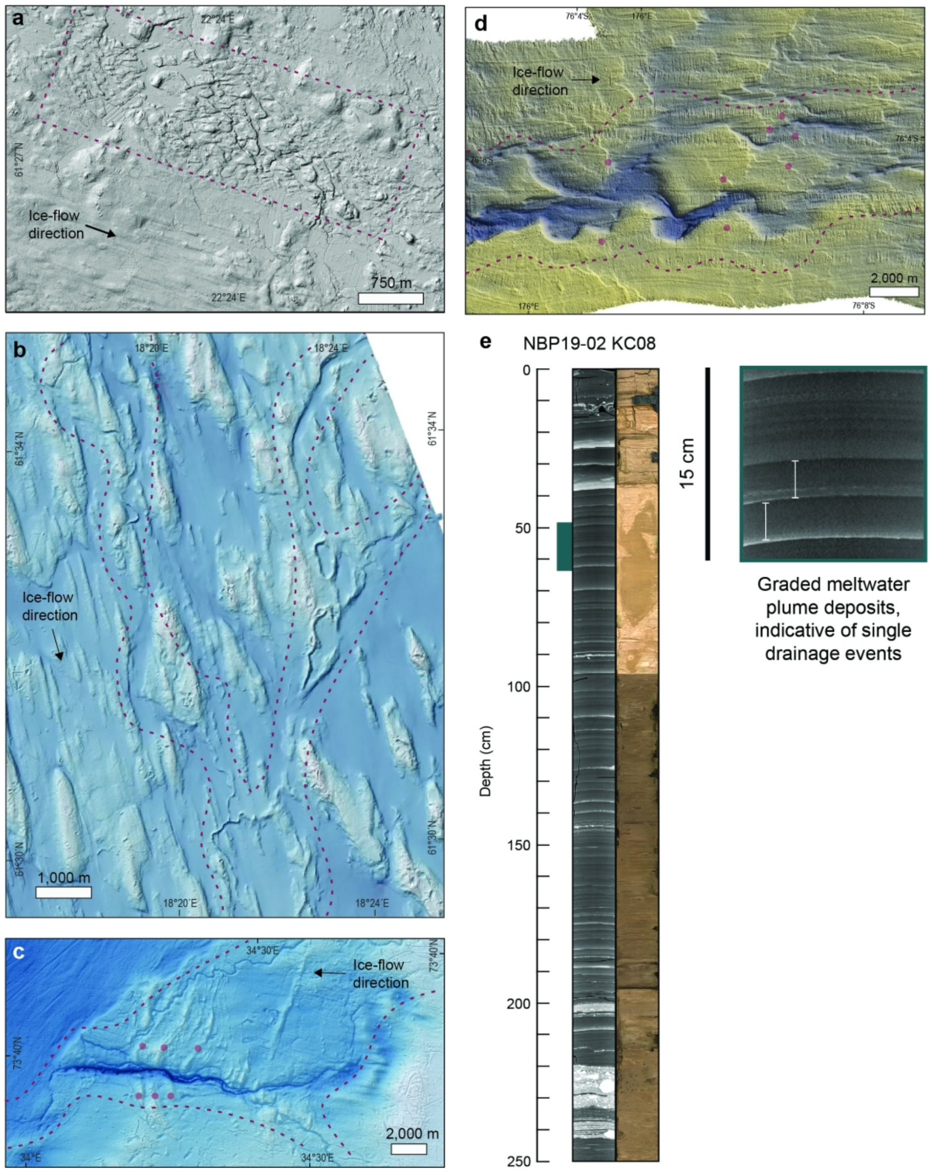

Fig. 1. (a) Murtoo pathway within glacially streamlined terrain in central Finland (Mäkinen et al. 2017; Ojala et al. 2019). Data: LiDAR-based DEM from the National Land Survey of Finland. (b) Meltwater channels and eskers drape and incise drumlins in the Bothnian Sea (Greenwood et al. 2017). Data: MBES-based DEM from the Swedish Maritime Administration. (c) Meltwater channel incised retreat moraines (red dots) on Thor Iversenbanken in the Central Barents Sea (Esteves et al., 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 et al. 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) Computed tomography (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 et al. 2022).

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