Annals of Glaciology

Letter

Cite this article: Miles KE, Hubbard B, Miles ES, Quincey DJ, Rowan AV (2022). Field-based research directions for investigating the interior of high-elevation debris-covered glaciers. *Annals of Glaciology* **63**(87-89), 107–110. https://doi.org/10.1017/aog.2023.21

Received: 4 October 2022
Revised: 11 January 2023
Accepted: 9 March 2023
First published online: 12 April 2023

Keywords:
Debris-covered glaciers; glacier hydrology; ice thickness measurements; ice temperature; ice velocity

Corresponding author:
Katie Miles; Email: kam64@aber.ac.uk

Field-based research directions for investigating the interior of high-elevation debris-covered glaciers

Katie E. Miles[1], Bryn Hubbard[1], Evan S. Miles[2], Duncan J. Quincey[3] and Ann V. Rowan[4]

[1]Centre for Glaciology, Department of Geography and Earth Sciences, Aberystwyth University, Aberystwyth, UK; [2]Swiss Federal Institute for Forest, Snow, and Landscape Research WSL, Birmensdorf, Switzerland; [3]School of Geography, University of Leeds, Leeds, UK and [4]Department of Earth Science, University of Bergen and Bjerknes Centre for Climate Research, Bergen, Norway

Abstract

The debris that covers the ablation areas of high-elevation debris-covered glaciers contributes to the distinctive features and processes occurring both on and within such glaciers. Despite recent advances, knowledge of the subsurface environments of high-elevation debris-covered glaciers is still extremely limited. In particular, targeted field-based data are needed to parameterise and refine the projections of these glaciers in numerical models. Here, we outline the current understanding of the internal properties of high-elevation debris-covered glaciers based on direct field-based methods and suggest future research directions for field-based studies.

1. Introduction

Mass loss from glaciers worldwide has accelerated over recent decades, compounding concerns relating to water security as mountain glaciers diminish (Immerzeel and others, 2020). Glacier behaviour at high elevation is modified by spatially variable factors, such as the dominant climatic regime, local relief, and the presence or absence of a debris cover. Debris-covered glaciers – those with a terminus mantled by a largely continuous layer of supraglacial debris (Miles and others, 2020) – occur across all glacierised mountain ranges. While supraglacial debris thicker than a few centimetres suppresses surface ablation, debris-covered glaciers are experiencing rates of net mass loss similar to their clean-ice counterparts (Brun and others, 2019). Spatial patterns of mass loss from debris-covered glaciers are more complex than those from climatically equivalent clean-ice glaciers, due to the presence of surface features (e.g. debris, ponds, and ice cliffs) that promote differential ablation and influence englacial conditions and glacier dynamics (Miles, ES and others, 2022). While supraglacial properties and processes at high-elevation debris-covered glaciers have been relatively well studied, englacial measurements are limited. This lack of empirical data raises challenges for the accurate representation of ice flow in models of glacier response to anticipated climate change.

Here, we first outline field-based studies that have contributed to current understanding of the interior of high-elevation debris-covered glaciers, focusing largely on Himalayan glaciers. Combining this with our own experience during the EverDrill project, we then suggest directions for future field-based research that will provide data to improve model projections of the behaviour of high-elevation debris-covered glaciers.

2. Summary of previous research on the interior of high-elevation debris-covered glaciers

2.1 Ice thickness

The thickness of debris-covered glaciers is likely affected by their distinctive mass balance and dynamic characteristics, and, in the Himalaya, their unique climatic and geomorphic context. Despite the importance of these data for calibrating glacier models, few direct measurements exist for high-elevation debris-covered glaciers, with only 11 records over High Mountain Asia in the recent GlaThiDa v3 database (Welty and others, 2020). Ground-penetrating radar (GPR) or radio-echo sounding has been used at Khumbu and Lirung Glaciers, Nepal Himalaya (Gades and others, 2000), and Koxkar and Southern Inylchek Glaciers, Tien Shan (Macheret and others, 1993; Zhen and others, 2013) to identify the glacier bed in the ablation area and thus estimate ice thickness. Gravimetric methods have given ice thickness profiles on Khumbu and Rongbuk Glaciers, located on the slopes of Mt. Sagarmatha (Chomolungma/Everest) (Sinica, 1975; Moribayashi, 1978). A limited number of boreholes (e.g. Miles and others, 2019*b*) or ice cores (e.g. Liu and others, 2009) have reached the bed of high-elevation debris-covered glaciers, yielding point measurements of ice thickness and allowing the installation of sensors to measure englacial properties through the full ice column.

2.2 Ice temperature

High-elevation debris-covered glaciers are likely to be thermally distinctive because of some combination of having: a high-elevation accumulation area; considerable mass accumulation via avalanching; an icefall; a quasi-stagnant tongue hosting numerous, often large, supraglacial ponds; a cover of surface debris of variable thickness; and, in some regions, a dominance of summer accumulation. The englacial temperature field is important for determining ice viscosity/softness and also the presence and location of temperate ice, which affects both glacier hydrology and motion, and is thus critically important in understanding how glaciers are responding to climate change. Direct measurements of ice temperature have been made at depths of <20 m in boreholes on Khumbu Glacier (Mae and others, 1975; Miles and others, 2021*b*) and Rongbuk Glacier (Sinica, 1975; TSECAS, 1975; Zhang and others, 2013), recording seasonally influenced ice temperatures. However, only a few measurements have been made in deeper boreholes, thereby recording longer-term ice temperature, such as in the accumulation areas of East Rongbuk Glacier (coldest −8.9°C at 108.8 m depth) (Hou and others, 2007), Gyabrag Glacier (−9.0°C at 68.5 m depth) (Liu and others, 2009) and Dasuopo Glacier, Chinese Himalaya (−13.8°C at the glacier bed, ~150-168 m depth) (Thompson and others, 2000). Deep englacial ice temperature measurements in the ablation area of Khumbu Glacier demonstrated a polythermal regime, with warm ice towards the bed and the coldest ice (only −3.3°C) at ~20 m depth in the upper debris-covered area (Miles, KE and others, 2018).

2.3 Ice deformation

Ice deformation is one of the primary glacier motion components and can be used to isolate basal sliding from net surface velocity. However, englacial ice deformation is difficult to measure directly; to our knowledge, no direct measurements of englacial ice deformation have been reported for high-elevation debris-covered glaciers. Instead, the ice deformation field of such glaciers has almost exclusively been reconstructed from theory or inferred from field-based structural mapping (which is hampered by the supraglacial debris covers of these glaciers). For example, interpretations of wave ogives on Khumbu Glacier have informed on ice motion through the Khumbu Icefall (Iwata and others, 1980; Hambrey and others, 2008), while planes interpreted as thrust faults on the same glacier have been used to infer ice pathways (Fushimi, 1977; Hambrey and others, 2008). Subsurface structural features were observed in boreholes on Khumbu Glacier, including rotated layers of primary stratification (layers of ice and debris) and relict layers of basally derived sediment, indicating a formerly more dynamic glacier regime (Miles, KE and others, 2022).

2.4 Englacial hydrology

The drainage and retention of meltwater within high-elevation debris-covered glaciers has important implications for the provision of water resources and the moderation of seasonal flow in rivers downstream. Khumbu and Ngozumpa Glaciers in the Nepal Himalaya are well studied in terms of their subsurface hydrology. Glacio-speleological studies have revealed features such as englacial cut-and-closure channels and an englacial water base-level controlled by the depth of an ice-marginal proglacial lake at the terminus of Ngozumpa Glacier (Gulley and Benn, 2007; Benn and others, 2017). Field-based investigations have inferred englacial meltwater storage and transit through Khumbu and Lhotse Glaciers, Nepal Himalaya (Rounce and others, 2017; Miles, ES and others, 2018) and englacial channels controlling the base level of closely located supraglacial ponds on a number of debris-covered glaciers in the Tien Shan (Narama and others, 2017). GPR surveys have located englacial and subglacial streams on Koxkar Glacier (Zhen and others, 2013), and dye-tracing studies have demonstrated subglacial to supraglacial meltwater transit and temporary meltwater storage in shallow englacial reservoirs within the debris-covered tongue of Khumbu Glacier (Miles and others, 2019*a*).

2.5 Sediment properties

Knowledge of englacial debris concentrations is necessary to quantify high-elevation debris-covered glacier erosion rates and to decipher the contribution of englacial debris melt-out to the supraglacial debris layer, as well as to test simplified sediment input approaches to numerical models (Rowan and others, 2015). Most such measurements are based on surface ice layers, such as an englacial debris concentration of 0.12% by weight over an area of 0.028 km^2 on Djankuat Glacier, Caucasus (Bozhinskiy and others, 1986). Deeper englacial debris concentrations, reconstructed from optical televiewer logs of boreholes up to 192 m deep on Khumbu Glacier, varied with depth, with a mean of 0.7% by volume across four boreholes and a maximum of 6.4% by volume in a borehole located nearest (~1 km) to the terminus (Miles and others, 2021*a*). Characterisation of debris facies (e.g. Hambrey and others, 2008) has informed on debris sources from surrounding hillslopes and relocation within the glacier system.

3. Future research directions

3.1 Englacial data for glacier evolution models

The rationale for recording field-based data from high-elevation debris-covered glaciers is to improve model projections of the future behaviour of these glaciers, the results of which are paramount for addressing regional issues such as water security (Immerzeel and others, 2020). Dynamic glacier models both calculate glacier mass balance over time and simulate ice flow and consequent geometric change (Zekollari and others, 2022). Although such models have been widely used in glaciology, their application to high-elevation debris-covered glaciers requires a bespoke approach (e.g. Rowan and others, 2015; Anderson and Anderson, 2016) due to: (i) the interaction of mountainous topography with regional weather systems; (ii) differential ablation regimes that depend on feedbacks between mass balance, ice flow, and debris transport, commonly involving a low- or even reverse-angle lower ablation area with abundant surface meltwater ponds; and (iii) complex stress regimes reflecting ice flow through high-relief topography, including extensive lateral and terminal moraines.

Empirical englacial data are most useful if available at sufficiently high spatial resolution to be able to guide, calibrate, and evaluate higher-order models, which can represent the geometrical and associated complexities of high-elevation debris-covered glaciers. Such a resolution would ideally involve detailed studies of individual glaciers, with data collected systematically over the glacier surface and with depth through the ice column, allowing the efficient gridding of data into three dimensions. In particular, observations on a single glacier should be made across the full glacier width at multiple elevations, as well as at locations where measurements might be expected to vary, such as either side of confluences with tributary glaciers and around supraglacial ponds. While more systematic measurements are needed from more glaciers to understand the expected spatial variation in all englacial features, comprehensive studies on a single glacier will be more valuable for modelling than sparse measurements across many glaciers. Large-scale, multi-component, integrated projects could allow detailed measurements on individual glaciers to be upscaled for model input.

The value of empirical datasets is increased further if they can be incorporated into models at physically meaningful temporal scales and resolutions. First, long-term decadal to centennial data are needed because glacier response time to adjust to external forcing is typically tens to hundreds of years, though their reaction time is typically multiple years. Second, seasonal weather, and hence mass-balance patterns, are so distinctive at many high-elevation debris-covered glaciers (e.g. monsoon-influenced areas) that models should aim to resolve at the seasonal as well as the annual scale. Sub-seasonal data collection could be facilitated by the use of methods that transmit data remotely, allowing data access and equipment monitoring through seasons that are more challenging for conducting fieldwork (e.g. winter or monsoon months).

3.2 Future research directions

Based on the above, we make the following suggestions for future research directions that would allow significant advances in modelling capabilities.

- **Ice thickness** measurements, which could be achieved through wider application of GPR systems mounted on helicopters (Pritchard and others, 2020) or uncrewed aerial vehicles (UAVs). Full-depth boreholes could evaluate such spatially extensive geophysical surveys by giving point-based ice thicknesses, as well as allowing further englacial measurements from borehole wall logs and ice cores. Enhanced community efforts to gather and compile unreported observations could further increase the coverage of such datasets (e.g. Welty and others, 2020).
- **Ice temperature** measurements of the basal thermal field at high-elevation debris-covered glaciers, which would inform on meltwater production and percolation, latent heat release, and the proportion of glacier motion by basal sliding. This could be recorded at high spatial resolution by borehole-based distributed temperature sensing using fibre-optic cables. The long-term installation of such cables in full ice depth boreholes in both the accumulation and ablation areas of high-elevation debris-covered glaciers would provide an extremely valuable dataset.
- **Basal motion**, resolved into basal sliding and ice deformation components by measuring: (i) surface velocity using a network of GNSS stations; and (ii) subsurface deformation through distributed acoustic fibre-optic sensing in full ice depth boreholes, calibrated with discrete borehole probes measuring ice tilt.
- **Mass balance** from seasonal and long-term accumulation records and trends, measured by combining meteorological stations with analysis of snow and firn cores from accumulation areas and/or borehole logging using an optical televiewer or a borehole camera.
- **Englacial meltwater storage**, both over the short term in shallow englacial reservoirs and over longer timescales from refreezing in crevasses, firn, or the supraglacial debris layer, to better predict timing of future meltwater delivery downstream. This could be achieved through glacier-scale water balance studies, supported by dye tracing to elucidate timescales of water storage in the system.
- **Runoff quality and quantity**, including pollution and sediment levels, measured through water sample analyses and long-term hydrological stations installed on proglacial streams.
- **Englacial sediment concentrations**, which could be measured directly by obtaining deep ice cores or indirectly by logging a borehole with an optical televiewer. Debris emergence could be further investigated by measuring the sediment concentration of shallow cores along a flowline.
- **Subglacial debris properties**, measured by sampling ice and sediment in the proglacial area and at the base of full ice depth boreholes.

Acknowledgements. This research was supported by the 'EverDrill' Natural Environment Research Council Grant awarded to Aberystwyth University (NE/P002021) and the Universities of Leeds and Sheffield (NE/P00265X). A. V. R. was supported by a Royal Society Dorothy Hodgkin Research Fellowship (DHF/R1/201113). We thank Himalayan Research Expeditions, Mahesh Magar, and Sagarmatha National Park for supporting fieldwork in Nepal.

References

Anderson L and Anderson R (2016) Modeling debris-covered glaciers: response to steady debris deposition. *The Cryosphere* **10**, 1105–1124. doi:10.5194/tc-10-1105-2016

Benn D and 5 others (2017) Structure and evolution of the drainage system of a Himalayan debris-covered glacier, and its relationship with patterns of mass loss. *The Cryosphere* **11**, 2247–2264. doi:10.5194/tc-2017-29

Bozhinskiy A, Krass M and Popovnin V (1986) Role of debris cover in the thermal physics of glaciers. *Journal of Glaciology* **32**(111), 255–266. doi:10.3189/S0022143000015598

Brun F and 6 others (2019) Heterogeneous influence of glacier morphology on the mass balance variability in High Mountain Asia. *Journal of Geophysical Research: Earth Surface* **124**, 1331–1345. doi:10.1029/2018JF004838

Fushimi H (1977) Structural studies of glaciers in the Khumbu region. *Seppyo* **8**, 30–39.

Gades A, Conway H, Nereson N, Naito N and Kadota T (2000) Radio echo-sounding through supraglacial debris on Lirung and Khumbu Glaciers, Nepal Himalayas. In: Debris-Covered Glaciers (Proceedings of a workshop held at Seattle, Washington, USA, September 2000). IAHS Publ. no. 264, 13–22.

Gulley J and Benn D (2007) Structural control of englacial drainage systems in Himalayan debris-covered glaciers. *Journal of Glaciology* **53**(182), 399–412. doi:10.3189/002214307783258378

Hambrey M and 5 others (2008) Sedimentological, geomorphological and dynamic context of debris-mantled glaciers, Mount Everest (Sagarmatha) region, Nepal. *Quaternary Science Reviews* **28**, 1084. doi:10.1016/j.quascirev.2009.04.009

Hou S and 9 others (2007) Summer temperature trend over the past two millennia using air content in Himalayan ice. *Climate of the Past, European Geosciences Union (EGU)* **3**, 89–95. doi:10.5194/cp-3-89-2007

Immerzeel W and 31 others (2020) Importance and vulnerability of the world's water towers. *Nature* **577**, 364–369. doi:10.1038/s41586-019-1822-y

Iwata S, Watanabe O and Fushimi H (1980) Surface morphology in the ablation area of the Khumbu Glacier. *Journal of the Japanese Society of Snow and Ice* **41**, 9–17. doi:10.5331/seppyo.41.Special_9

Liu Y, Hou S, Wang Y and Song L (2009) Distribution of borehole temperature at four high-altitude Alpine glaciers in Central Asia. *Journal of Mountain Science* **6**, 221–227. doi:10.1007/s11629-009-0254-9

Macheret Y and 5 others (1993) Tolshchina i stroenie lednika juzhnyj Inyl'chek po dannym radiozondirovanija (thickness and structure of southern Inylchek glacier from the data of radio echo sounding). *Materialy Glyatsiologicheskikh Issledovanii* **77**, 86–97.

Mae S, Wushiki H, Ageta Y and Higuchi K (1975) Thermal drilling and temperature measurements in Khumbu Glacier, Nepal Himalayas. *Journal of the Japanese Society of Snow and Ice* **37**, 161–169.

Miles ES and 8 others (2018) Glacial and geomorphic effects of a supraglacial lake drainage and outburst event, Nepal Himalaya. *The Cryosphere* **12**, 3891–3905. doi:10.5194/tc-2018-152

Miles KE and 6 others (2018) Polythermal structure of a Himalayan debris-covered glacier revealed by borehole thermometry. *Scientific Reports* **8**, 1–9. doi:10.1038/s41598-018-34327-5

Miles KE and 5 others (2019a) Surface and subsurface hydrology of debris-covered Khumbu Glacier, Nepal, revealed by dye tracing. *Earth and Planetary Science Letters* **513**, 176–186. doi:10.1016/j.epsl.2019.02.020

Miles KE and 5 others (2019b) Instruments and methods: hot-water borehole drilling at a high-elevation debris-covered glacier. *Journal of Glaciology* **65**(253), 882–832. doi:10.1017/jog.2019.49

Miles KE and 5 others (2020) Hydrology of debris-covered glaciers in High Mountain Asia. *Earth-Science Reviews* **207**, 103212. doi:10.1016/j.earscirev.2020.103212

Miles KE and 6 others (2021a) Continuous borehole optical televiewing reveals variable englacial debris concentrations at Khumbu Glacier, Nepal. *Communications Earth & Environment* **2**, 1–9. doi:10.1038/s43247-020-00070-x

Miles KE and 5 others (2021b) Data report: Seasonal cold-wave propagation into the near-surface ice of debris-covered Khumbu Glacier, Nepal. *Frontiers in Earth Science* **9**, 1–4. doi:10.3389/feart.2021.715129

Miles KE, Hubbard B, Miles E, Quincey D and Rowan A (2022) Internal structure of a Himalayan debris-covered glacier revealed by borehole optical televiewing. *Journal of Glaciology*, 1–12. doi:10.1017/jog.2022.100.

Miles ES, Steiner JF, Buri P, Immerzeel WW and Pellicciotti F (2022) Controls on the relative melt rates of debris-covered glacier surfaces. *Environmental Research Letters* **17**, 064004. doi:10.1088/1748-9326/ac6966

Moribayashi S (1978) Transverse profiles of Khumbu Glacier obtained by gravity observation. *Seppyo, Glaciological Expedition of Nepal, Contribution No. 46*, pp. 21–25.

Narama C and 6 others (2017) Seasonal drainage of supraglacial lakes on debris-covered glaciers in the Tien Shan mountains, Central Asia. *Geomorphology* **286**, 133–142. doi:10.1016/j.geomorph.2017.03.002

Pritchard HD and 5 others (2020) Towards bedmap Himalayas: development of an airborne ice-sounding radar for glacier thickness surveys in High-Mountain Asia. *Annals of Glaciology* **61**(81), 1–11. doi:10.1017/aog.2020.29

Rounce D, Byers A, Byers E and McKinney D (2017) Brief communications: observations of a glacier outburst flood from Lhotse Glacier, Everest area, Nepal. *The Cryosphere* **11**, 443–449. doi:10.5194/tc-2016-239

Rowan A, Egholm D, Quincey D and Glasser N (2015) Modelling the feedbacks between mass balance, ice flow and debris transport to predict the response to climate change of debris-covered glaciers in the Himalaya. *Earth and Planetary Science Letters* **430**, 427–438. doi:10.1016/j.epsl.2015.09.004

Sinica A (1975) Basic features of the glaciers of Mt. Jolmo Lungma region, southern part of the Tibet autonomous region, China. *Scientia Sinica* **18**, 106–130.

Thompson L and 5 others (2000) A high-resolution millenial record of the South Asian monsoon from Himalayan ice cores. *Science* **289**, 1916–1919.

TSECAS (1975) *Monograph on Mount Qomolangma scientific expedition (1966–1968): modern glacier and geomorphology, in the ablation area in the ablation area. Tibetan Scientific Expedition of the Chinese Academy of Sciences*. Science Press.

Welty E and 11 others (2020) Worldwide version-controlled database of glacier thickness observations. *Earth System Science Data* **12**, 3039–3055. doi:10.5194/essd-12-3039-2020

Zekollari H, Huss M, Farinotti D and Lhermitte S (2022) Ice–dynamical glacier evolution modeling – a review. *Reviews of Geophysics* **60**, 000754. doi:10.1029/2021rg000754

Zhang T and 7 others (2013) Observed and modelled ice temperature and velocity along the main flowline of East Rongbuk Glacier, Qomolangma (Mount Everest), Himalaya. *Journal of Glaciology* **59**(215), 438–448. doi:10.3189/2013JoG12J202

Zhen W, Shiyin L, Shiqiang Z and Honglang X (2013) Internal structure and trend of glacier change assessed by geophysical investigations. *Environmental Earth Sciences* **68**, 1513–1525. doi:10.1007/s12665-012-1845-2