Journal of Glaciology

Letter

Cite this article: Gage HJM, Eyles CH (2024). Greater than the sum of its parts: optical remote sensing and sediment core data provide a holistic perspective on glacial processes. *Journal of Glaciology* 1–7. https://doi.org/10.1017/jog.2024.7

Received: 25 May 2023
Revised: 20 January 2024
Accepted: 22 January 2024

Keywords:
glacial sedimentology; paleoclimate; remote sensing

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Greater than the sum of its parts: optical remote sensing and sediment core data provide a holistic perspective on glacial processes

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Abstract

In this letter we make the case that closer integration of sediment core and passive optical remote sensing data would provide new insights into past and contemporary glacio-sedimentary processes. Sediment cores are frequently used to study past glacial processes and environments as they contain a lengthy geochemical and sedimentological record of changing conditions. In contrast, optical remote sensing imagery is used extensively to examine contemporary glacial processes, including meltwater dynamics, glacial retreat, calving, and ice accumulation. While paleoenvironmental data from sediment cores and optical remote sensing imagery are rarely used in tandem, they are complementary. Sediment core records are spatially discrete, providing long-term paleoenvironmental proxy data which require assumptions about environment-sediment linkages. Optical imagery offers precise, spatially extensive data to visualize contemporary processes often limited in their temporal extent. We suggest that methodologies which integrate optical remotely sensing with sediment core data allow direct observation of processes interpolated from sedimentological analysis and achieve a more holistic perspective on glacial processes. This integration addresses the limitations of both data sources and can achieve a stronger understanding of glacier dynamics by expanding the spatiotemporal extent of data, reducing the uncertainty of interpretations, and broadening the local analyses to regional and global scales.

Introduction

Understanding the scale, effects and record of glacial processes is essential to assess the impacts of climate change on the cryosphere. However, most research is focused either on relatively local scale, but temporally lengthy glacial and/or sedimentological investigations, or on spatially extensive yet temporally limited studies utilizing remote sensing methodologies. Recent advances in remote sensing technology have expanded the breadth and precision of data for the study of glacial environments (Kaushik and others, 2019). Passive optical remote sensing, which detects wavelengths of solar radiation reflected by the Earth's surface, has become ubiquitous for its accessibility and the fact that it can provide data across large spatial scales. In particular, satellite-based optical imagery is now widely available and can be used by those with limited expertise in remote sensing, and without the financial and technological constraints posed by other remote sensing methodologies.

To date, optical remotely sensed data have been employed in glacial environments to provide information about glacier area (Zhao and others, 2020), accumulation and ablation rates, mass balance gradients (Bisset and others, 2020), debris cover (Holobâcă and others, 2021), terminus retreat (Foga and others, 2014; Zhu and others, 2014), ice flow velocity (Fahnestock and others, 2016), glacier topography (Garg and others, 2017), glacial landform characteristics/formation (Chandler and others, 2016), and meltwater dynamics (Wufu and others, 2021), among other applications. Given that field-based cryosphere research provides information on a much smaller scale than optical imagery platforms, remote sensing can fill temporal and spatial knowledge gaps while monitoring on an appropriate scale and resolution to achieve a holistic understanding of glacial processes (Bhardwaj and others, 2016). This is especially important in areas such as the Himalaya, where there is a paucity of field data due to research constraints (Singh and Thadani, 2015; Singh and others, 2016).

Developments in the availability of remote sensing imagery have also broadened the scope of data obtained from process-oriented glacial research (Bhardwaj and others, 2016). In remote glacierized areas, it may be difficult to collect field data frequently enough to establish a continuous record of glacier processes (Bishop and others, 2000; Sam and others, 2016; Bhardwaj and others, 2016; Telling and others, 2017). Remote sensing has facilitated change detection studies at a fine temporal interval which can be used to monitor such things as glacial hazards and to evaluate the impacts of contemporary climate change on glacial processes (Jain and Mir, 2019; Vale and others, 2021; Gu and others, 2023).

To study changes in glacial processes over time, paleoenvironmental data can be obtained from the analysis of late Quaternary depositional environments. Here we focus on data from sediment cores, which offer insight into a variety of glacial processes which shift the timing, type, and amount of sediment that is delivered to and deposited in the proglacial basin (Bakke and Paasche, 2011). Paleoenvironmental data obtained from sediment cores are useful for answering the questions 'What?' and 'When?'. For example: What was the sediment provenance and depositional environment? When was the sediment produced, transported, and deposited? What are the seasonal or annual dynamics of glacial processes? This is especially important for comparing phenomena over long timescales when there are shifts in frequency or magnitude that produce changes in sedimentological characteristics.

One of the advantages of employing sediment cores is that they provide a wide range of sedimentological data, such as grain size, sediment lithology, sorting, lamination, and structural characteristics, as well as geochemical data, each of which offer information about separate glacial processes (Bakke and Paasche, 2011). Hence, a single sediment core that records variations in sediment input over time can potentially give a comprehensive picture of locally changing conditions in the depositional environment (but see Van Wyk de Vries and others, 2023). Paleoenvironmental records obtained from sediment cores have been used for a variety of applications, including the study of meltwater dynamics (Striberger and others, 2012), subglacial and proglacial weathering (Takano and others, 2015), glacial retreat (Avery and others, 2019), and water contamination (Zhu and others, 2020). Paleoenvironmental analysis of terrestrial landforms and sediment exposures can also provide valuable information about past environments and depositional processes although they are often limited by the interpretability, length, and temporal scale of the available record (Benn and Owen, 2002; Barr and Lovell, 2014).

There is a growing awareness that modern geoscience necessitates an interdisciplinary approach which permits geoscientists to solve new scientific problems. To this end, remote sensing techniques have been increasingly combined with in situ field measurements to estimate glacier characteristics, particularly mass balance (e.g. Clark, 1997; Rivera and others, 2002; Negi and others, 2012; Karušs and others, 2022). Outcrop logging and geomorphological mapping have also been combined successfully with remote sensing data to extend the spatial scale of observations and inform understanding of the relationship between glacial processes and landforms (Boulton and others, 1999; Chandler and others, 2016, 2018; Davies and others, 2017; Lovell and others, 2018; Ewertowski and Tomczyk, 2020; Storrar and others, 2020; Boston and others, 2023). In turn, remote sensing imagery can be used for landsystem analysis to provide important geomorphological insights, and has been combined with stratigraphic logging and numerical dating to investigate landform evolution during successive glacial advances/retreats (Boulton and Clark, 1990; Livingstone and others, 2010; Gribenski and others, 2016).

A significant opportunity that has not been fully exploited to date is the integration of optical remote sensing data (namely multispectral imagery) and paleoenvironmental data obtained from sediment cores. While practitioners of glacial geomorphology and of remote sensing have employed integrated methods since the early development (i.e. 1970s, 1980s) of satellite-based imagery, these methods were largely restricted to the analysis of data from glacial landforms or sediment sections (Sugden, 1978; Punkari, 1980). This continues to be the case despite the opportunities that exist (e.g. Straneo and others, 2019) to combine optical remote sensing datasets with data from sediment cores, which are widely used to study glacial processes and past environmental conditions. As the quality and accessibility of remotely sensed data has enhanced, integration of these specific datasets will provide a more holistic picture of glacial sedimentary processes on a variety of temporal and spatial scales.

The case for combining optical remote sensing and sediment core data

Optical remote sensing and paleoenvironmental data derived from sediment cores have complementary characteristics (Table 1). This means that a multi-method approach may address the conceptual and technical limitations of each data source (e.g. proxy interpretation, sensor calibration) while augmenting the spatiotemporal extent of the combined dataset. An integrated approach offers the opportunity to link past and present analogs to answer a broader range of questions on contemporary glacial processes and long-term glacial activity. Combining optical remote sensing and sediment core data improves the scale, scope, and interpretability of these datasets.

Scale

Sediments deposited over decades to tens of thousands of years can be dated with relatively high precision to provide annual (or in some cases, sub-annual) data (e.g. Stansell and others, 2013). However, the data which can be gleaned from these measurements are inherently restricted by uncertainty in the dating of the core and the rate of sedimentation (Croudace and others, 2019; Lisiecki and others, 2022). Remote sensing imagery is temporally precise, with a high frequency of collection so can be used to analyze glacial processes at more continuous intervals with high temporal certainty. Thus, coarse resolution processes interpreted from sediment cores can be confirmed over short timescales using remote sensing. Likewise, paleoenvironmental data obtained from sediment cores offer much longer temporal extent than satellite-based remote sensing, for which data have only been available since the mid-late twentieth century (Figure 1).

In terms of spatial scale, optical remote sensing imagery is extensive and can provide comprehensive coverage over an entire glacier and proglacial basin. Sediment cores can be difficult and costly to extract, which may limit the quantity of data that can be obtained from a site of interest (Bakke and Paasche, 2011). The inaccessibility of many glacial environments, and the fact that lengthy sediment records are typically restricted to proglacial lakes, also place constraints on the spatial extent of paleoenvironmental datasets derived from sediment cores alone (Bakke and Paasche, 2011). Obtaining data from spaceborne sensors alleviates the challenges of intensive field data collection and can provide

Table 1. Complementary characteristics of remotely sensed and sediment core data

Characteristics	Optical remote sensing data	Sediment core data
Spatial extent	Discrete to continuous, spatially extensive	Discrete, spatially restricted
Temporal extent	Short (days to decades), high precision	Long (decades to epochs), poor precision
Conventional applications	Contemporary glacial processes	Paleo-glacial processes
Interpretation	May require ground-truthing and calibration	Reliant upon assumptions about proxy-process extrapolation
Data availability	On-demand	Months to years to collect and process

https://doi.org/10.1017/jog.2024.7 Published online by Cambridge University Press

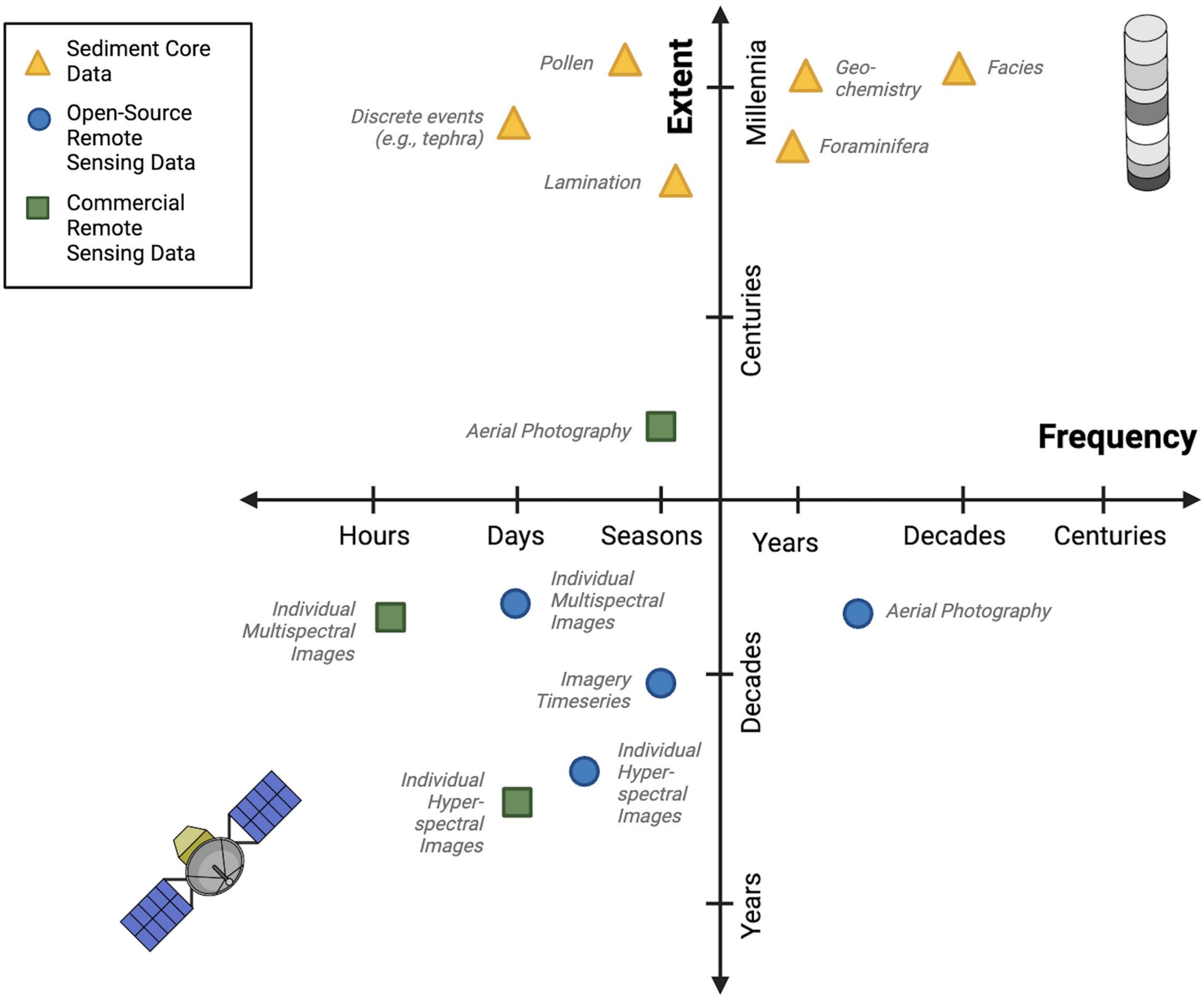

Figure 1. Temporal extent and frequency of optical remote sensing and sediment core data. Each point represents a category of information that can be extracted from remotely sensed or sediment data. Positions are represented conceptually; there is variability in both the extent and frequency of these data sources based on the methodology employed.

coverage over areas that otherwise cannot be assessed (Bishop and others, 2000; Bhardwaj and others, 2016).

Interpretation

Interpreting paleoenvironmental data requires practitioners to make assumptions about how sediments are related to glacial processes in situ. For example, geochemical sediment proxies have nuanced interpretations which can shift based on the depositional environment (Croudace and Rothwell, 2015). Sediments preserve an indirect record of environmental conditions at the time of their deposition, which means that well-supported interpretations of geochemical sediment proxies make inherently speculative conclusions about why and how glacial processes have occurred (Bakke and Paasche, 2011).

In this respect, remote sensing is especially valuable because it can supply information about the context in which sediments have been deposited (e.g. to illustrate the environmental conditions responsible for varve deposition in proglacial lakes; Zolitschka and others, 2015; Van Wyk De Vries and others, 2022). Information about contemporary processes observed in remotely sensed imagery can be used to verify whether historical phenomena interpreted from paleoenvironmental records continue to occur.

One of the drawbacks of utilizing remote sensing data is that they often require ground-truthing to verify the precision of imagery interpretations. For instance, when using spectral indices to delineate glacier extent, seasonal snow, water bodies, or clouds may be incorrectly identified because they have similar index values to glacial ice (Holobâcă and others, 2021; Racoviteanu and others, 2022). This is because optical remote sensors only measure reflectance within discrete wavelength bands which may not be precise enough to discriminate surfaces with similar spectral properties (Bhardwaj and others, 2016). Remote sensing data also require calibration to eliminate the effects of atmospheric and ground-based scattering which impact bottom-of-atmosphere reflectance measurements (Hall and others, 1990; Burns and Nolin, 2014; Jawak and others, 2022). Ultimately, these limitations mean that field data are frequently required to verify the validity of remote sensing measurements (Jones, 1983; Brandelik and others, 1998). While sediment core records collected from lacustrine or marine environments do not provide information about specific ground cover spectral indices or atmospheric corrections, they *can* be used to supplement remote sensing data by providing confirmation that changes interpreted in optical imagery have indeed occurred in the glacial environment, such as shifts in the composition of glacierized and nonglacierized surfaces (e.g. Gage and others, 2022a, 2022b).

Scope

A promising outcome of combining datasets with complementary spatial and temporal extents is the ability to extend analyses from

https://doi.org/10.1017/jog.2024.7 Published online by Cambridge University Press

local to regional and global scales. Local scale observations can be upscaled by linking glacial processes or landforms that are well understood from sediment cores to remote sensing signatures (e.g. spectral indices) which can be identified more broadly across the landscape (Bamber and Rivera, 2007; Jennings and others, 2022). An advantage of this approach is that by aligning sediment core data at the local scale with remotely sensed imagery signatures it is possible to infer sedimentological changes that might be occurring across the broader landscape.

The integration of sedimentological core analysis and optical remote sensing may also broaden the conceptual scope of research to numerous questions in glacial geology which are difficult to answer using one of these techniques alone. Investigations into the temporal variability of processes linking glacier advance/retreat and sediment and landform development are particularly well suited to this approach. For instance, examining relationships between changing ice velocity or ice recession rates and sediment characteristics can be achieved by comparing glacial motion in imagery timeseries to sediment core records. Other topics relating to sediment production, such as the effect of changing ice thickness, margin configuration, and seasonal/annual changes of the sediment load associated with meltwater discharge could also be investigated by integrating datasets.

Combining optical remote sensing and paleoenvironmental research

There are several examples in the literature which pioneered an approach integrating optical remote sensing and paleoenvironmental data obtained from sediment cores (also see Schiefer and others, 2007; Schiefer and Gilbert, 2008; Dowdeswell and others, 2015; Flink and others, 2018; Noormets and others, 2021; Piret and others, 2021). López-Moreno and others (2017) studied the recent development of proglacial lakes in Peru's Cordillera Blanca using short lake sediment cores. X-ray fluorescence and grain size analysis allowed the identification of two distinct sedimentary units consistent with deposition in a high- and low-energy environment, respectively. Multispectral Landsat imagery was then used to link these changes to shifts in glacial extent, which indicated that the adjacent glacier partially covered the lake in 1975 and retreated rapidly during the mid-1980s and 1990s due to warm and dry El Niño conditions. Similarly, preliminary work from Gage and others (2022a, 2022b) using X-ray fluorescence on three sediment cores from Lake Shallap in the Cordillera Blanca demonstrate that sediment influx (Zr/Ti) and iron enrichment (Fe/Ti) proxies had increased between the early 20th century and present. The authors examined spectral indices of iron (ferrous iron index) and glacier cover (NDSI) over pairs of Sentinel-2 images and determined that areas of high glacial retreat were spatially associated with areas of ferrous iron enrichment, particularly during warm El Niño years. This suggests that climate change has accelerated glacial retreat and exposed iron-rich bedrock which is now contaminating meltwater.

Van Wyk de Vries and others (2022) examined the sediment dynamics of a proglacial lake in the Southern Patagonian Icefield by assessing the composition of 47 sediment cores. Rhythmic alternation between coarse-grained, calcium-enriched dark laminae and fine-grained calcium-depleted light laminae would suggest seasonal deposition according to meltwater flux dynamics, with a higher summer sediment input and lower winter input. However, assessment of Sentinel-2 multispectral imagery demonstrated that relative suspended sediment concentration was higher in the winter than the summer. This dissuaded the authors of the notion that sediment dynamics were driven solely by the seasonal cycle of sediment delivery and revealed that seasonality in lake mixing contributed to the deposition of annual varves in the sediment.

Andresen and others (2012) collected optical imagery and three sediment cores from the Sermilik Fjord to reconstruct a record of calving activity at the Helheim Glacier in Greenland over the past 120 years. The authors used satellite and aerial imagery to confirm that sand deposition in the sediment cores, a proxy for ice-rafted debris, is concurrent with glacial retreat. These data indicate that glacial retreat in the imagery intensifies during 5–10-year calving episodes and that the Helheim Glacier is highly responsive to atmosphere-ocean variability over short timescales. Campagne and others (2015) performed micropaleontological and geochemical analyses on a sediment core to reconstruct ocean conditions in the Mertz Glacier polynya. The authors observed an approximately 70-year periodicity between conditions with abundant open-water diatoms, high Ti, and large grain size, and conditions with high sea-ice indicators, low Ti, and low grain size. To investigate the potential cause for this cyclicity, Giles (2017) employed a complementary remote sensing approach using a sequence of images and determined that glacial advances cause the glacier tongue to calve periodically, which controls the development of the polynya.

Considerations and limitations

For those wishing to adopt integrated methodologies, optical remote sensing techniques are low-hanging fruit – optical imagery is financially and technologically accessible and does not require intensive field data collection. Appropriate study sites are those with good optical imagery coverage in locations where sediment cores can be reasonably obtained. Integrative methodologies should also aim to examine time periods which lend themselves to combining optical imagery and sediment core data, such as the late Holocene (particularly the 'Anthropocene') during which there is remote sensing coverage and paleo-processes can be documented. Weaknesses or inadequacies of the specific datasets being examined should be clearly identified. For remote sensing datasets, this might include uncertainty in assessing a multispectral index which behaves similarly for multiple surface cover types, or the limited temporal extent of available imagery. Challenges with sediment core datasets could include difficulties interpreting a particular geochemical sediment proxy, establishing accurate sedimentation rates, or dealing with discontinuities which disrupt interpretations of the paleoclimatic record. These challenges should be leveraged while designing the methodology to be used so that complementary analyses of optical imagery and sediment core data can minimize the identified uncertainties.

We propose that the integration of optical remote sensing and sediment core data will achieve a more holistic understanding of past and current environmental conditions than the examination of each dataset individually. However, these combined datasets are not a panacea capable of explaining all glaciological processes, nor can they be successfully integrated in all cases. Linking optical imagery and sediment core data may prove difficult when the paleoenvironmental record available from sediments is much lengthier (e.g. thousands of years) than the remote sensing record, or when both datasets do not have coverage of the same study area. Obtaining sediment cores remains logistically and financially challenging, particularly for lengthy records in hostile field environments.

Moreover, limitations to the precision of analytical tools for sediment cores, such as X-ray fluorescence scanners, may restrict the temporal resolution of paleoenvironmental records such that events occurring over the remote sensing record cannot be observed in both datasets. Numerical dating methods also limit

https://doi.org/10.1017/jog.2024.7 Published online by Cambridge University Press

the precision with which imagery timeseries and sediment core records can be aligned. A conceptual challenge of this approach may be to correctly interpret remote sensing and sediment core data in unison because the combined information they provide (e.g. multispectral indices, geochemical proxies) has multiple, context-dependent interpretations. The ease with which integration can be achieved will rely on correctly identifying sources of uncertainty, such as sensor viewing characteristics and calibration in optical imagery and dating uncertainty in sediment cores.

Further advances in remote sensing technology will alleviate some of these challenges. The continued development of imaging platforms will provide a much wider array of spectral bands with precise interpretations, improve data accessibility, and will enhance temporal and spatial resolution to allow alignment of sediment core and remote sensing datasets. The application of hyperspectral imagery is especially promising as it can be used more precisely to identify lithological characteristics (Ting-ting and Fei, 2012). Increasing the precision of numerical dating and paleoenvironmental analyses used in sedimentological investigations (e.g. resolution of x-ray fluorescence scanners to resolve events occurring within the extent of imagery timeseries) will also enhance our ability to align multiple datasets. Numerical and conceptual models may prove valuable in bridging the gap between remote sensing and sediment core data as each provides insight about different aspects of the same overall process (e.g. Dowdeswell and others, 2015; Giles, 2017).

Conclusion

Optical remote sensing and sedimentological core analyses used to interpret paleoenvironmental conditions are complementary in nature. When examined alone, sedimentary records derived from cores require careful interpretation and are temporally restricted in their resolution, which may make it difficult to connect past and contemporary processes. In contrast, remote sensing approaches used to determine environmental conditions and/or changes in contemporary glacial processes have limited temporal scope and often require additional ground-truthed data. Hence, given the rapid increase in the availability of open-access optical imagery there is a timely opportunity to employ integrated methods to fill the knowledge gaps that exist when remotely sensed data or sedimentologic records are examined in isolation.

The examples we provide, and the growing body of literature combining remote sensing with other traditional glaciological and sedimentological methods, suggest that such an approach is feasible to improve our understanding of glacial environments and their response to climate change. These datasets are best integrated in scenarios which: (i) investigate glacial processes that operated in the recent past (decades to centuries); (ii) employ novel paleoenvironmental sediment proxies, or those with conflicting interpretations, which benefit from validation with remotely sensed data; (iii) are constrained by the limited availability of sediment core or remote sensing data; (iv) examine processes which vary or operate across different temporal and spatial scales; and/or (v) have been studied locally and require contextualization to draw conclusions about processes operating regionally or globally.

While recent research has begun combine these approaches (e.g. López-Moreno and others, 2017; Gage and others, 2022a, 2022b; Van Wyk De Vries and others, 2022), there still remain many opportunities to integrate remotely sensed data and paleoenvironmental data obtained from sedimentary cores. Future work should seek to combine these data from the outset to enhance the breadth and quality of information available to investigate the record of current and past processes in glacial environments.

Acknowledgements. This research was funded by a Global Science Initiative Grant from the Faculty of Science, McMaster University. We thank reviewers Harold Lovell and Max Van Wyk de Vries and Chief Editor Hester Jiskoot for their insightful comments on the manuscript.

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https://doi.org/10.1017/jog.2024.7 Published online by Cambridge University Press