First empirical assessment of ice content from Himalayan rock glaciers.

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Climate warming in the Himalaya threatens glaciers and permafrost, with severe implications for the future sustainability of the region's natural 'water towers' and connected ecological systems and human infrastructure. Recent work in high mountain environments has highlighted how rock glaciers are prevalent and contain globally valuable water supplies. Yet, over the Himalaya, information regarding their number, spatial distribution, morphometric characteristics and water content are scarce. Here, we present the first measured assessment of ice content in any Himalayan rock glacier. We use InSAR and Ground Penetrating Radar (GPR) surveys, respectively, to assess the current movement and ice content of a large rock glacier at Gokyo, central Nepal. This landform is situated at over 4700 m elevation and we show that parts of it are currently moving downslope at 75-100 cm per year; a figure in line with other rock glacier velocities in high arid mountains. This suggests that the rock glacier contains solid buried ice, and this is confirmed by our GPR surveys. We demonstrate the presence of massive ice units up to 250 m in length and 28 m in thickness underlies the rock glacier surface, representing an estimated total of up to 3.01 ×10^5 m^3 of freshwater equivalent. We have recently reported that there are over 25,000 rock glaciers in the Himalayas. If the Gokyo rock glacier is representative for the region, then these landforms are likely to contain significant amounts of ice, and therefore will be of great hydrological value to downstream regions as climate change progresses and the buried ice slowly melts.

Key words: rock glacier ice content water Himalaya

Introduction

Over 54,000 glaciers across the Himalaya and other parts of High Mountain Asia (Bajracharya et al., 2015) regulate the region's streamflow (Azam et al., 2021; Nie et al., 2021). Yet, these glaciers are now melting rapidly and losing 19 Gt a^{-1} (Shean et al., 2020). This ice loss is jeopardising future water supplies critical for up to 2 billion people (Immerzeel et al 2010; Miles et al., 2021; Yao et al 2022) and affects sensitive montane and glacier-fed ecosystems (Leng et al., 2023). Remote sensing technologies provide robust estimates of the distribution, characteristics and transformation of glaciers across the region (Bolch et al., 2012), and have driven projections of their response to climate change (Rounce et al., 2023) and resultant streamflow (Lutz et al., 2014; Huss and Hock, 2018). However, geomorphological processes in these warming high mountains pose a complexity as they are conducive to forming debris-covered areas over the region's glaciers.

Between 10% and 20% of the total glacier area in the Himalaya is estimated to be debris covered (Scherler et al., 2011; Kaab et al., 2012; Scherler et al., 2018) and recent assessments suggest this area is expanding (Herreid & Pellicciotti, 2020). Contrary to assumptions of reduced ablation due to debris cover (Mattson et al., 1993; Kayastha et al., 2000), many of these debris-covered glacier areas are losing mass at similar rates to debris-free ice (Maurer et al., 2019). However, researchers have argued that down-wasting debris-covered glaciers can transition to rock glaciers (e.g. Whalley, 1974; Monnier and Kinnard, 2015; Anderson et al., 2018), and we have argued that this is occurring in the Himalaya (Jones et al. 2019a). Indeed, we recently identified over 25,000 rock glaciers extending over 3747 km^2 of the Himalaya region (Jones et al., 2021; Harrison et al., 2024).

Emergent, contemporary and avalanche-derived rockfall debris increases the concentration of supraglacial material as Himalayan glaciers down-waste, and this progressively protects relict buried ground ice, and drives the development of rock glacier formation in incipient proglacial zones and in deglacierising tributary catchments (Owens and England, 1998; Herreid & Pellicciotti, 2020). Owing to the insulating properties of the thicker debris cover, rock glacier ground ice is thought to be climatically more resilient than debris-covered glacier ice, where debris thickness often varies from several centimetres to a few meters at the terminus (Anderson et al., 2018). Consequently, the hydrological importance of rock glaciers compared to that of debris-covered and debris-free glaciers may increase under future climate warming (Harrison et al., 2021). Using remote sensing approaches we have inferred that, in Nepal, rock glacier ice fractions of ~73% typically could represent storage of 10^6 m^3 w.e. in individual rock glaciers (Hu et al., 2023). However, there remains no empirical information on rock glacier ice content in any part of the Himalaya, which obscures our understanding of their likely future contribution to the region's water supplies. Therefore, assessments of the ice content within Himalayan rock glaciers are urgently needed.

Here, to provide the first empirical measurement of Himalayan rock glacier ice content, we target Gokyo rock glacier in the Khumbu Himal, Nepal (27°56'27.72"N; 86°41'39.11"E), to the east of Ngozumpa Glacier (Benn et al., 2000) and 23 km to the southwest of Mt. Everest (Figure 1a,b). This rock glacier extends over 1.28 km^2, and ranges between ~4700 and 5300 m a.s.l.. It is representative both in size and geomorphological context (Figure 1c) to other rock glaciers in the region (Jones et al., 2019; 2021; Hu et al., 2023), comprising a steep lake-terminating ablating terminus (Figure 1d) at 4716 m. a.s.l. and a hummocky boulder-covered surface with considerable local relief (Figure 1e). It has many of the characteristics of active rock glaciers including a steep terminus and lateral margins, and ridge and furrow surface topography indicating active movement (RGIK 2022). To investigate whether the rock glacier was active and contained sub-surface ice, our approach combined remote sensing interferometry (Hu et al., 2023) and geophysical ground penetrating radar (GPR: Kniesel et al., 2008; Monnier & Kinnard, 2015).

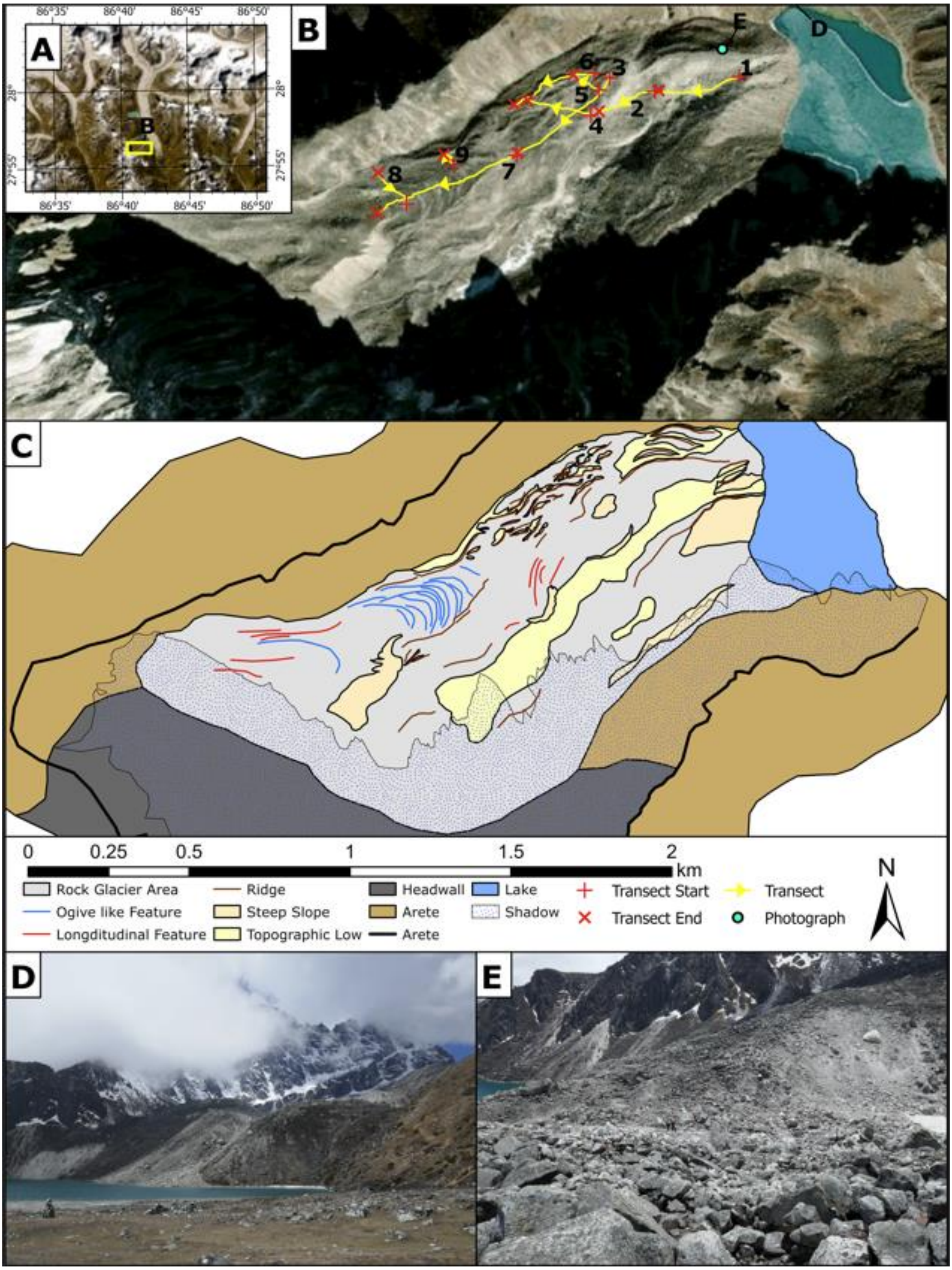

Figure 1: Gokyo Rock glacier. A: Regional map, B: 2023 Satellite image, source: *Maxar* 1.5 m Arcpro basemap, C: geomorphological interpretation, D: Front of Gokyo rock glacier, E: The boulder-covered, high-relief surface of Gokyo rock glacier (Sherpa assistants, Laxmi and Bir, for scale).

Figure 1: (A) regional location map of Gokyo rock glacier; (B) position of GPR survey lines overlain on the Maxar 1.5 m ArcGISPro basemap image, 2023; (C) geomorphological interpretation of the catchment; and oblique image of (D) the rock glacier terminus and (E) characteristic boulder-covered, high-relief surface.

Results:

We derived an interferogram from Sentinel-1 images acquired on 6 and 18 July, 2021. Low-quality pixels with coherence smaller than 0.3 were masked out. Wrapped and unwrapped interferograms obtained from these InSAR observations are shown in Figure 2, along with the LOS and downslope velocities of the rock glacier. A prominent cluster of high velocity is visible in the central region of the rock glacier. For the downslope velocity calculations, approximately 70% of the pixels are considered valid. Within specific areas of the rock glacier, the maximum downslope velocity reaches 1ma^{-1}, with the 75th percentile downslope velocity of around 0.30 ma^{-1}.

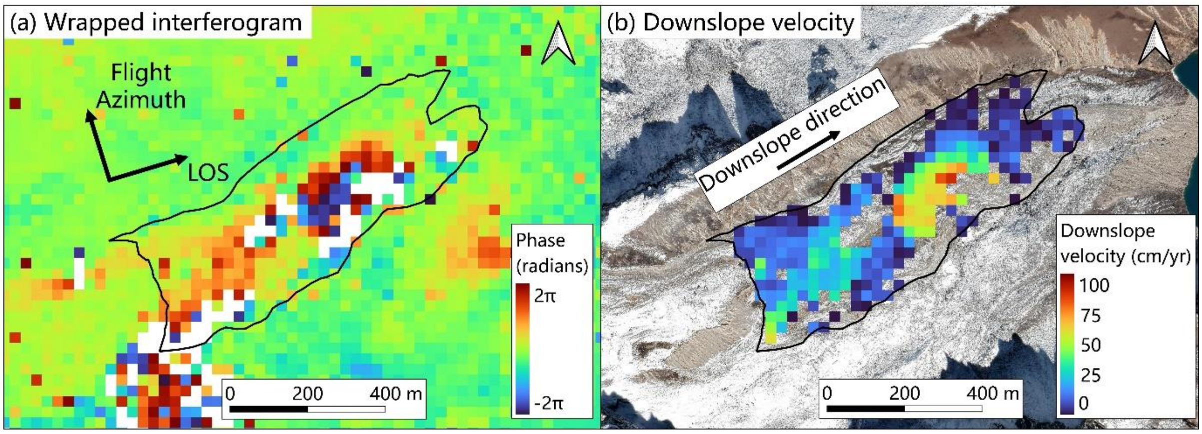

Figure 2 (a) Wrapped interferogram, (b) unwrapped interferogram, (c) line-of-sight velocity, and (d) downslope velocity of Gokyo rock glacier. The interferogram is formed using Sentinel-1 images acquired on July 6th and July 18th, 2021. The low-quality pixels with coherence smaller than 0.3 are masked out. The background is Google Earth image.

A total of nine GPR transects, between 50 m and 450 m in length, were collected with a 50 MHz antennae (Figure 1B). These transects imaged subsurface features to depths equivalent to two-way travel times of 600 ns (~50 m) (Figure 3a). Due to the difficult and often inaccessible nature of the terrain on this rock glacier high resolution gridded transects were not possible. Below the near-surface, subsurface interfaces likely indicating dielectric contrasts between debris or ice-containing units are quasi-linear, but typically discontinuous (Figure 3b). These we interpret to be debris layering, with unit boundaries dipping gently up-, down- or cross-rock glacier, indicative of poorly sorted debris. This semi-coherent layering we suggest corresponds to the progressive, episodic burial of supersaturated permafrost by mass movement (Berthling et al., 2000; Jones et al., 2019a). The dipping nature of these sediment structures is likely to have occurred due to the internal deformation, leading to a formation of internal structures akin to “nestled spoons” seen near the termini of valley glaciers (Berthling et al., 2000; Jones et al., 2019a; Jennings and Hambrey, 2021).

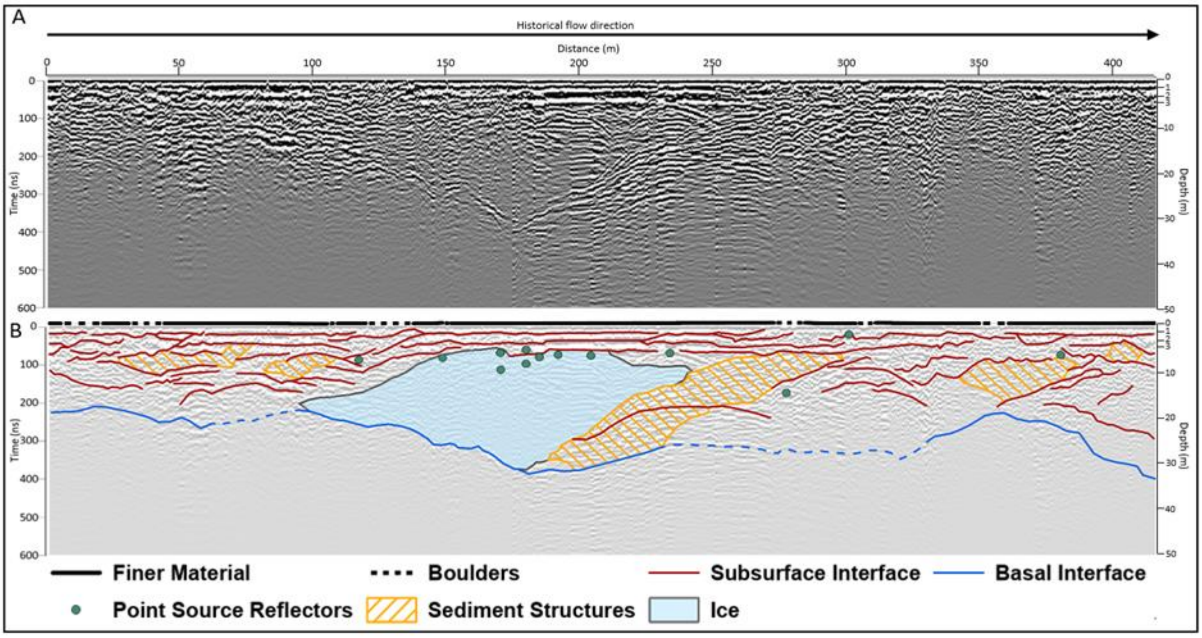

Figure 3: (A) Example processed radargram for Transect 1+2 and (B) the associated interpretation. Indicative depths between < 3 m calculated from velocity values for moraine (0.095 m ns^{-1}) and between 3-50 m from velocity values for glacier ice (0.167 m ns^{-1}).

Crucially, in our radargrams, we identified units of buried massive ice that are characterised by zones of weaker reflections (Figure 3B). In these units, analysis of hyperbolae arising from point source reflectors confirmed radar velocities approaching ~0.167 m ns^{-1}, as commonly quoted for glacier ice (Reynolds, 2011). We found no evidence of strong reflectors indicative of voids, large boulders or channels in these buried ice units, but from the radargram signal we inferred the ice potentially contains some irregularly distributed debris or varied water content. The buried ice unit near the rock glacier’s terminus, below a debris layer between 3 and 9 m, is ~150 m in length, with a maximum thickness of 28 m. At higher elevation on the Gokyo rock glacier, a second buried ice unit extends 250 m up-rock glacier, with a thickness of 17.5 m, is overlain by 2.5 to 6 m of debris. The cross-feature transects, coupled with the surface topography, show that both units of buried ice extend ~150m across the rock glacier.

The base of the rock glacier was identified in the radargram as a quasi-linear, semi-continuous reflector with few reflections beneath it (see Figure 2a). Given the variability in debris structure and size observed at the surface and in the subsurface, we estimate moraine debris energy propagation velocities between 0.08 and 0.113 m ns^{-1}, and our observed 0.167 m ns^{-1} for buried ice to infer a maximum rock glacier thickness of 31.5 (±10.71) m.

Recognising the rock glacier’s buried ice as a freshwater reservoir, and employing the topographically corrected radargrams as visual guides, we approximated the buried ice units as semi-ellipsoids to determine their volumes. Our calculations show Gokyo Rock Glacier contains between 2.12×10^5 and 3.88×10^5 m^3 of massive buried ice. Accounting for the typical englacial sediment content in debris-covered glacier ice of 6.4% by volume, and a density of 830 kg m^{-3} to account for air bubbles (Miles et al, 2021), we suggest Gokyo Rock Glacier contains at least 1.64×10^5 m^3 water equivalent (w.e.). This represents a specific water storage of between 0.12 and 0.23 m w.e. within the rock glacier. However, we note that this reservoir estimate represents a minimum as our evaluation excludes any interstitial water stored within the sediment-rich structures and zones within the landform, which may range from between 20% and 60% by volume (Wagner et al. 2021) given the rock glacier lies above the characteristic Himalaya permafrost limit.

Discussion

Our study represents the first empirical data evaluating ice content from any of the rock glaciers in the Himalayas and also represents the highest altitude rock glacier in the world on which such investigations have been carried out. Gokyo rock glacier’s high altitude raises the chances of permafrost occurrence such that the feature is more likely to contain interstitial ice in addition to buried ice masses than rock glaciers at lower elevations. We have used InSAR data to show that the feature is moving downslope, and GPR to map the presence of massive buried ice units within the landform. We show that these techniques can be used on Himalayan rock glaciers to map stored freshwater volumes and, as with our previous research, has focused attention on the hydrological resources that rock glaciers represent.

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Contributions

SH developed the initial research idea, obtained funding, undertook fieldwork with MP, and wrote the first draft of the paper. TIF, MP, YH, LL, ZS, KA and RL provided Interferogram and GPR data, data analysis and co-wrote later drafts of the paper.