

Revising supraglacial rock avalanche magnitudes and frequencies in Glacier Bay National Park, Alaska

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ARTICLE INFO

Keywords:

Supraglacial debris
Rock avalanche
Magnitude frequency
Climate change

ABSTRACT

The frequency of large supraglacial landslides (rock avalanches) occurring in glacial environments is thought to be increasing due to feedbacks with climate warming and permafrost degradation. However, it is difficult to (i) test this; (ii) establish cause–effect relationships; and (iii) determine associated lag-times, due to both temporal and spatial biases in detection rates. Here we applied the Google Earth Engine supraglacial debris input detector (GERALDINE) to Glacier Bay National Park & Preserve (GLBA), Alaska. We find that the number of rock avalanches (RAs) has previously been underestimated by 53 %, with a bias in past detections towards large area RAs. In total, GLBA experienced 69 RAs during 1984–2020, with the highest frequency in the last three years. Of these, 58 % were deposited into the accumulation zone and then sequestered into the ice within two years. RA sources clustered spatially at high elevations and around certain peaks and ridges, predominantly at the boundary of modelled permafrost likelihood. They also clustered temporally, occurring mainly between May and September when air temperatures were high enough to initiate rock-permafrost degradation mechanisms. There was a chronic background debris supply from RAs, with at least one RA occurring in all but nine years; however, a debris rich period during 2012–2016 was driven by three large RAs delivering 44 % of all (1984–2020) debris (by area). Comparable investigation of slope-failures in other remote currently glaciated regions is lacking. If RA rates are similar elsewhere, especially the bias towards emplacement onto/into accumulation zones, their contribution to glacial sediment budgets has been globally underestimated.

1. Introduction

Glaciers are fed with debris by the full range of landslide processes from small scale rock falls to large scale failures such as rock avalanches (Deline et al., 2014, 2021). Rock avalanches (RAs) are high magnitude, perceived low frequency, predominately bedrock slope failures that generate volumes of material typically $>10^6 \text{ m}^3$ (Dufresne et al., 2016). RA sediment supply is as highly fragmented debris emplaced as a point source, perhaps equivalent to many years of ‘normal’ chronic and more spatially distributed supply from valley walls. For example, the debris volume of the Lyell Glacier supraglacial RA in South Georgia, was estimated to be equivalent to 93 years of ‘normal’ supraglacial supply

(Gordon et al., 1978). RA surface morphology typically shows common geomorphic and semi-diagnostic features so they can be remotely identified (Hewitt, 1999; Shugar and Clague, 2011). RAs occur in areas of high relief and in many landscapes have been shown to be highly effective erosive agents, generating substantial sediment fluxes and extensive valley fills (Korup et al., 2010). They are ultimately a key component in determining landscape geomorphology and sedimentary budgets (Korup et al., 2004; Korup, 2005, 2012; Uhlmann et al., 2013). Determining their magnitude and frequencies in glacial environments through time is potentially an important, yet largely unquantified, flux to glacial debris supply (Ekström and Stark, 2013) and mountain erosion above downcutting ice. Establishing this flux is important due to the

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<https://doi.org/10.1016/j.geomorph.2023.108591>

Received 12 January 2023; Accepted 16 January 2023

Available online 24 January 2023

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control of debris supply on glacier melt (e.g., Reznichenko et al., 2010), glacier velocity (e.g., Shugar et al., 2012), and the export of limiting nutrients like silica and iron into extra-glacial ecosystems (e.g., Death et al., 2014; Hawkins et al., 2014, 2017).

Relief, slope angle, and active tectonics are known contributors to RA hotspots in glacial environments (e.g., Jibson et al., 2006; Coe et al., 2018). Recent research has suggested that the frequency of RAs in these environments, outside of those clusters linked to earthquakes, is increasing due to the pressures of climate warming on permafrost, and, as glaciers retreat, the exposure and contested idea of de-buttressing of high-relief slopes (e.g., Huggel et al., 2012; Ravelle et al., 2017; Dai et al., 2020; Chiarle et al., 2021). However, many RAs may also be explained by accumulating rock slope stresses over multiple glacial cycles (Grämiger et al., 2018). Establishing the true magnitude-frequency of RAs and any paraglacial forcing is therefore complex (McColl, 2012; Ekström and Stark, 2013; Grämiger et al., 2017). In non-glacial and/or formerly glaciated environments the rate of detection through time can also be linked to deposit size and the rate at which the deposits diagnostic features are eroded or modified (Sanhueza-Pino et al., 2011), as well as being reliant on correct identification of landslide provenance, rather than a glacial origin (Hewitt, 1999). However, even in highly erosive/active environments, diagnostic features that reveal former RAs can persist; in fluvial environments some RA dams can cause knickpoints identifiable in the geological record (Korup et al., 2010; Fan et al., 2020). In glacial environments, however, detections of past supraglacial RAs are primarily limited to the time they are visible on the glacier surface, or imaged in the ice column using geophysical methods (Dunning et al., 2015). RAs deposited in glacier accumulation zones can be rapidly covered by fresh or windblown snow, and ingested into the ice (Dunning et al., 2015), with as yet unknown persistence as a recognisable, single event deposit within the glacier as it moves. Those deposited in the ablation zone remain visible, but their deposits can: (i) deform through differential ice motion (Shugar and Clague, 2011); and (ii) redistribute due to contrasting ablation rates at the boundary between clean ice and the thicker, melt-reducing deposit (Reznichenko et al., 2011; Uhlmann et al., 2013). Within or on debris-covered glaciers, RA identification is predominantly only possible through geomorphic analyses or lithological differences (Deline, 2009; Shugar and Clague, 2011; Deline et al., 2014). When supraglacial and englacial RAs emerge as pro-glacial/terminus deposits, they arguably contain unequivocal evidence of past RA processes (Reznichenko et al., 2012) but require extensive sampling campaigns and microscopic sedimentological analyses to determine their origin and age. Our current understanding of past supraglacial RA frequencies and importance is therefore temporally biased and insufficient (Ekström and Stark, 2013). This makes any postulated climatic-driven upturn in frequencies difficult to establish in an environment that may be the most sensitive to climate warming-driven changes (Coe, 2020). Incorporating these size (larger events are easier to identify) and visibility (landslides in some dynamic environments are quickly lost (Dunning et al., 2015; Higman et al., 2018)) biases into inventories provides unrealistic estimates of the frequencies of supraglacially deposited RAs. The data available indicate that RA size and frequency are increasing (Schlögel et al., 2011; Coe et al., 2018; Hibert et al., 2019; Bessette-Kirton and Coe, 2020) (Kyrgyz Tien Shan and Glacier Bay, Alaska, respectively), but that it is likely that severe underestimates of slope activity exist in large components of mountainous landscapes (Hibert et al., 2019).

Detection of contemporary RAs in glacial environments has typically occurred in three main ways: eye-witness reporting (Deline et al., 2014), seismic detection (Ekström and Stark, 2013), and manual analysis of optical satellite imagery (Bessette-Kirton and Coe, 2016; Uhlmann et al., 2013). Eye-witness reports of events are low, particularly in remote glacial areas, unless societal/economic damage has occurred (e.g., Hubbard et al., 2005; Schneider et al., 2014; Cox et al., 2015). Seismic detections can locate events and give exact timing and information on emplacement dynamics, but both long period (e.g., Ekström and Stark,

2013) and high frequency (e.g., Zimmer and Sitar, 2015; Dietze et al., 2017; Fuchs et al., 2018) seismic wave detection techniques for identifying slope-failures have their limitations. Long-period seismic waves only identify those with a strong seismic signal (magnitude (M) > 5.0) and often with a ~ 100 km² radius location accuracy (Ekström and Stark, 2013). High-frequency seismic wave detections of landslides are complicated by numerous non-landslide sources for high-frequency waves, making identification difficult and time-consuming (Hibert et al., 2019). Manual analysis of satellite imagery is resource-intensive and can be time-consuming for the operator if a regional scale, multi-temporal investigation is being undertaken. This results in a frequently adopted approach whereby images with minimal cloud cover between spring and autumn (where these seasons are distinct) are analysed (Bessette-Kirton and Coe, 2016) as detection chances are high with minimal new snow fall. However, this temporally restricted approach can overlook RAs occurring throughout the year that can then be sequestered into glacial ice rapidly after emplacement (Dunning et al., 2015). Detection of the La Perouse RA in Glacier Bay National Park & Preserve (GLBA), Alaska (Coe et al., 2018), is a good example of this. This RA occurred in late winter (16/02/2014) and entrained a large amount of snow and ice. This made the contrast between it and the surrounding ice low, and as a result the entire deposit was only clearly visible in four Landsat images before it was sequestered. The upper half of the deposit was sequestered within a month, the deposit toe was visible until November 2014. If the deposit did not straddle the summer snow line, and had been emplaced entirely above, it is unlikely it would have been detected by manual image analysis. Coe et al. (2018) acknowledge that they may miss autumn/winter events, or, erroneously date them to the following spring if they reappear.

Due to the limitations of existing detection techniques, comprehensive supraglacial RA inventories are rare, often with focus on just one RA (e.g., Cox et al., 2015), or multiple RAs triggered by an earthquake (i.e., an event inventory, e.g., Jibson et al., 2006). Recently a regional cluster of large RAs was detected in GLBA using manual mapping of time-series Landsat imagery with the purpose of creating a baseline from which changes in supraglacial landslide, frequency, magnitude and mobility could be determined, and possibly linked to climate change. Bessette-Kirton and Coe (2016) created this 1984–2016 RA inventory using 104 Landsat images (at least one image between May–October per year) of 30-m resolution, finding a total of 24 RAs ranging from 0.1 km² to 22.2 km² using optical contrast of debris to snow and characteristically lobate RA emplacement forms. Coe et al. (2018) used this dataset to analyse magnitude, mobility, and frequencies of the mainly spring and summer detected RAs and to investigate potential triggers. The events were found to ‘cluster’ temporally, with the three clusters showing increasing size and mobility over time: 1984–1986, 1994–1995 and 2012–2016. Examination of potential causes controlling the timing and sizes of RAs in GLBA revealed increasing air temperatures and the subsequent degradation of rock-permafrost as the most likely processes for triggering RAs.

It has been known for many years that bedrock permafrost containing ice-filled joints contributes to maintaining slope stability (e.g., Bjerrum and Jorstad, 1968). Prolonged warm events such as the 2003 and 2015 heatwaves in the European Alps provided strong evidence for permafrost warming as a trigger for rock slope failures, as these summers were also characterised by an exceptional number of rockfalls from permafrost slopes (Gruber et al., 2004; Ravelle et al., 2017). Legay et al. (2021) simulated bedrock temperature for 209 rockfalls (2007–2015) and statistically compared their locations to 209,000 random artificial events at observed rockfall locations in the Mont Blanc massif. Results confirmed that warm permafrost areas (i.e., > -2 °C) are prone to slope failures, indicating this temperature is a critical threshold to trigger instabilities. The role of permafrost degradation in triggering far larger, deeper, rock-slope failures and RAs is less easily resolved. The often remote and spontaneous nature of slope failures means it is difficult to definitively prove permafrost degradation as a final trigger for slope

failures (Legay et al., 2021) – permafrost warming at depth is a long-term response and likely more insensitive to shallow, seasonal warming variability that has been shown to trigger smaller failures (Ravanel et al., 2017). However, work in Norway has been able to link the onset and deformation history of large rock-slope failures that may perhaps transition into RAs to degrading permafrost (Hilger et al., 2021). Coe et al. (2018) link the GLBA RAs to the combined effects of both short term (months) and long-term (millennia) warming as the simplest explanation for their observed increases in triggering. In the European Alps and Norway, both monitoring and modelling have shown that degrading permafrost over multiple timescales can be linked to current observations of decreasing slope stability and/or increasing creep rates in large deep-seated bedrock failures. Some of these failures may have initiated several thousand years ago, and, some can fail suddenly as RAs (Mamot et al., 2021; Hilger et al., 2021), with the initial precursory long-term creep towards this final failure unknown or only identified in back analyses. The numerical modelling work of Mamot et al. (2021) highlights two major points relevant for our work, (i) a non-linear response of stability to warming, with increased displacements (absolute and relative) when approaching the melting point of ice, (ii) for steep ($>50^\circ$) slopes the factor of safety falls below 1 when warmed from -4°C to between -3 and -0.5°C , temperatures closely linked to lower permafrost boundaries and documented landslide release zones (Coe et al., 2018; Fischer et al., 2012; Ravanel et al., 2010).

Our current understanding of bedrock permafrost degradation mechanisms involves decreasing uniaxial compressive strength and subsequently tensile strength ($> -10^\circ\text{C}$) (Mellor, 1973; Dahlström, 1992; Dwivedi et al., 1998; Ning et al., 2003), initiation and growth of shear planes ($> -5^\circ\text{C}$), which are then controlled by ice-mechanics, increasing susceptibility to atmospheric temperatures (Krautblatter et al., 2013), and the weakening of the stiffness and strength of ice-filled joints ($> -1.5^\circ\text{C}$) (Davies et al., 2001; Mamot et al., 2018). Advective heat transfer by water percolation is also a key control on the morphology of ice-filled joints (Hasler et al., 2011), and percolating water can increase hydrostatic pressures in ice-sealed fractures (Krautblatter et al., 2013). Determining the role of hydrostatic pressures in slope failures is difficult, however, due to a lack of in-situ monitoring and coupled thermo-hydromechanical models (Krautblatter et al., 2012). However, modelling (e.g., Matsuoka and Sakai, 1999; Deline et al., 2011; Frauenfelder et al., 2018) and statistical analysis of climate variables (Allen and Huggel, 2013; Luethi et al., 2015; Paranzunzio et al., 2016) provide strong evidence that this is the case.

Few events are recorded in glacier accumulation zones, which are usually backed by higher, colder slopes than ablation zones. To determine with any confidence that RA occurrence in relation to permafrost, mobility, or other changing environmental variables, we need complete inventories. Currently, a question that could be asked is: Is the lack of known accumulation zone RAs a function of limited occurrence, or, of limited detections? The balance between accumulation zone and ablation zone RA sources can allow us to make inferences about the required conditions above glaciers to trigger RAs. In addition, if RAs are under-reported in accumulation zones, they potentially have a more important role in generating englacial and subglacial sediment than is currently attributed to basal erosion and entrainment.

Here we formally hypothesise that if accumulation zones RAs are under detected, then use of the Google Earth Engine supraglacial debris input detector (GERALDINE) (Smith et al., 2020) will correct this issue. GERALDINE is a new, free-to-use, cloud-based tool that utilises the computing capabilities of Google Earth Engine (Gorelick et al., 2017) to eliminate the disadvantages of manual RA detection and streamline the detection process. We show the added value of GERALDINE with a reanalysis of the manually mapped (Bessette-Kirton and Coe, 2016) GLBA RA hotspot. We find and present a substantive difference in identified RAs between their inventory and our more complete GERALDINE inventory.

2. Method

2.1. Detection

GERALDINE utilises an image stack using every cloud-free pixel of every available Landsat image within a user-defined area and timeframe of interest. Using these data, GERALDINE creates a simple map from which a user can identify and verify new supraglacial RA deposits $>0.05\text{ km}^2$ (see Smith et al. (2020) for details of the tool). It cannot, however, detect RA debris deposited onto already debris-covered glacier ice, therefore preventing detection of events characterised by multiple failures, nor can it utilise cloudy imagery. It is therefore important to acknowledge that, even with GERALDINE, RA detection rates are likely to be underestimates. We ran GERALDINE annually between 1984 and 2020 using a study area identical to the one utilised by Bessette-Kirton and Coe (2016) and Coe et al. (2018). In total, 1853 Landsat images were analysed by GERALDINE (for breakdown of annual and monthly image frequency and average scene cloud cover see Fig. S1), with 1393 of these images analysed over the same period as Bessette-Kirton and Coe (2016), in contrast to the 104 they utilised. All output maps with automatic debris detections were manually analysed along with the Landsat scenes to verify RA deposit detections, based on commonly agreed characteristics: lobate and elongated, and discrete source area association (Deline et al., 2014). We refer to all landslide deposits as RAs in this study, despite most newly identified events being relatively small in areal extent (i.e., 71 % were $< 0.5\text{ km}^2$), due to the characteristics described above. Despite this abundance of smaller RAs, our dataset is directly comparable to that of Bessette-Kirton and Coe (2016) because we only identify one RA that was smaller (0.097 km^2) than their smallest RA deposit (0.11 km^2). Any RA candidates that were not part of the Bessette-Kirton and Coe (2016) inventory were verified, digitised, and their time window of occurrence was identified using the Google Earth Engine Digitisation Tool (GEEDiT) (Lea, 2018). To do this, we specified the location and the year of the RA within GEEDiT, which then returned all the Landsat images that fit these criteria. Then, we analysed each image to determine the window of occurrence, before digitising the deposit, and exporting it into a geographic information system (GIS). Minimum and maximum elevations of each RA deposit and aspect of the headscarp were calculated using the Interferometric Synthetic Aperture Radar (IFSAR) digital elevation dataset (5 m resolution) collected in summer 2012 (USGS, 2018) as per Bessette-Kirton and Coe (2016).

Landslides were manually mapped in their entirety using GEEDiT, with polygons including both the source and deposit to ensure continuity between our dataset and that of Bessette-Kirton and Coe (2016). Source zones in GLBA are often small (in two dimensions (2D)) in comparison to the deposits due to the exceptionally steep rock-wall sources. It is also difficult to accurately delineate the boundary between source and deposit zone due to the glaciated nature of the region, providing minimal contrast between the different RA zones without an accurate post-event digital elevation model (DEM) (Bessette-Kirton et al., 2018).

2.2. Magnitude frequency

We calculated the magnitude-frequency relationship of our RA inventory using the method of Tanyaş et al. (2018). This is done by binning RAs based on their deposit size and plotting these bins against the corresponding frequency-density values to create a frequency-area distribution curve (Tanyaş et al., 2018). For the GLBA RA inventory, we do not report the landslide-event magnitude (mLS) parameter as per Tanyaş et al. (2018) method because our RAs were not triggered by a singular event at a defined point in time (e.g., earthquake). Typically, the frequency-area distributions of medium and large landslides are characterised by a power-law relationship (e.g., Malamud et al., 2004). To assess the validity of the power-law fit to our data, a p -value indicating hypothesis plausibility was calculated using the method of

Clauset et al. (2009). This method was also used to assess uncertainties by Tanyaş et al. (2018).

2.3. Rock avalanche relationship with temperature

To assess RA relationship with temperature, we used 2-m, above-ground, monthly-mean (derived from mean daily temperatures) temperature data from the ERA5-Land reanalysis (Muñoz-Sabater, 2019). This dataset is an improvement of the land component of the ERA5 reanalysis dataset (Hersbach et al., 2020), which is created using observations of atmospheric conditions, predominantly from satellites. These data are used as an input into the European Centre for Medium-Range Weather Forecasts (ECMWF) integrated forecasting system (Cy41r2). ERA5-Land has a spatial resolution of 0.1×0.1 degrees (Muñoz-Sabater, 2019), which equates to pixel sizes of about 11.1×5.8 km in the study region. Each cell uses the average elevation of the Shuttle Radar Topography Mission 30-m DEM as altitude, and is corrected using a daily lapse rate derived from ERA5 (Muñoz-Sabater et al., 2021). RAs occurred in 21 of the ERA5-Land cells. To retrieve temperature, we used the ERA5-Land cell that the RA source occurred within, and the date the RA was first visible in Landsat satellite imagery, as the date of occurrence, or the actual event date if known (four RAs). This window of occurrence (gap between the image where the RA was not visible and was visible) averages 39 days, but varies between 7 and 272 days (Table S1). The nature of RAs in the study area is that RAs are typically only visible over their summer of occurrence and are then buried by winter snowfall and/or advected into the ice indefinitely, as documented elsewhere (Dunning et al., 2015). As a result, we have confidence that our visible dates are close to their actual occurrence dates (generally within 30 days) and are therefore suitable for assessing temperature relationships using monthly-mean average temperatures. For RAs that occur on the first day of the month, this is imperfect, but for RAs that occur at the end of the month, this works well. There is therefore no perfect solution to this issue due to the format of the ERA5-Land data. Temperature anomalies were calculated by extracting monthly temperature data from the corresponding ERA5-Land cell within which the RA occurred, averaging these data between the years of 1984 and 2020 as a reference window, and then subtracting the RA occurrence month's temperature from this average. For example, a RA that occurred within ERA5-Land cell 14 in June 2015 would have all June temperatures for cell 14 averaged, and then the June 2015 cell 14 temperature would be subtracted from this average. This gives a positive value if the RA occurrence month's temperature was above average and a negative value if the temperature was below average.

In addition to the ERA-5 temperature data, we used the 30 arc-second (~ 1 km grid) global permafrost zonation index (PZI) (Gruber, 2012) to investigate the relationship between RAs and permafrost likelihood. This dataset was derived by modelling the established relationships between air temperature and permafrost occurrence using the NCAR-NCEP reanalysis (Kalnay et al., 1996) and CRU TS 2.0 (Mitchell et al., 2004). The permafrost zonation index output is a qualitative map of permafrost likelihood spanning from permafrost existing in only the most favourable conditions, to permafrost existing in almost all conditions.

2.4. Earthquakes as a trigger

We used an identical method to Coe et al. (2018), which is a modified version of Keefer (1984) and Jibson (2013), to determine if any RAs were caused by earthquakes, instead of using newer methods (e.g., Havenith et al., 2016). This is because the newer methods require detailed information on lithology and antecedent rainfall conditions, which we do not have for GLBA. We downloaded data for all $>M$ 4.0 earthquakes within 100 km of the study area, from the USGS Earthquake Catalog (<https://earthquake.usgs.gov/>). Only earthquakes $>M$ 4.0 were selected because earthquakes under this threshold are characterised by

an insignificant area over which they can trigger mass movements (Keefer, 1984; Jibson, 2013).

3. Results

3.1. Frequency and size

Using GERALDINE, 27 RAs were identified between 1984 and 2016 that were not included in the original inventory created by Bessette-Kirton and Coe (2016) (Figs. 1A, 2A, and Table 1). This equates to a 53 % underestimation of the number of RAs using manual detection. Of the 27 additional RAs identified, 21 occurred in accumulation areas. In addition, 26 of them were recorded in just a 14-year period between 1997 and 2009 (Fig. 1A). This fills in the majority (57 %) of the 'quiet' time periods where no RA events were previously identified (Coe et al., 2018). Instead of clusters of RA activity, we find that a consistent RA frequency characterises the region during our study window. Our new inventory shows that only nine of the 33 years analysed featured no RA activity, with just one quiet period between 1989 and 1993. However, this quiet period had the lowest image availability over the study period, so RAs may have occurred, but inadequate images prevented detection (Fig. S1). With the additional RAs we identified between 1984 and 2016, average frequency for this time period increases from 0.7 to 1.5 RAs yr^{-1} . Updating the inventory to include 2017–2020 identifies an additional 18 RAs. In this 4-year period, 2020 experienced the highest RA event frequency of the entire 37-year period, with eight RAs (8 RAs yr^{-1}). Including these four additional years increases the average annual RA frequency to 1.9 RAs yr^{-1} . RA frequency never exceeded four events per year until 2018 and 2020, when we see six and eight events, respectively. In total, 69 RAs were detected between 1984 and 2020 (Table 1).

Bessette-Kirton and Coe (2016) estimated the total RA deposit area between 1984 and 2016 at 55 km^2 ; however, we find an additional 13.3 km^2 of RA debris coverage over this time period, a 19 % underestimate (Fig. 1B and Table 1). An additional 12 km^2 of RA debris coverage was identified between 2017 and 2020. Using this updated RA debris coverage (80.3 km^2), this equates to 0.04 % of the GLBA glaciated area

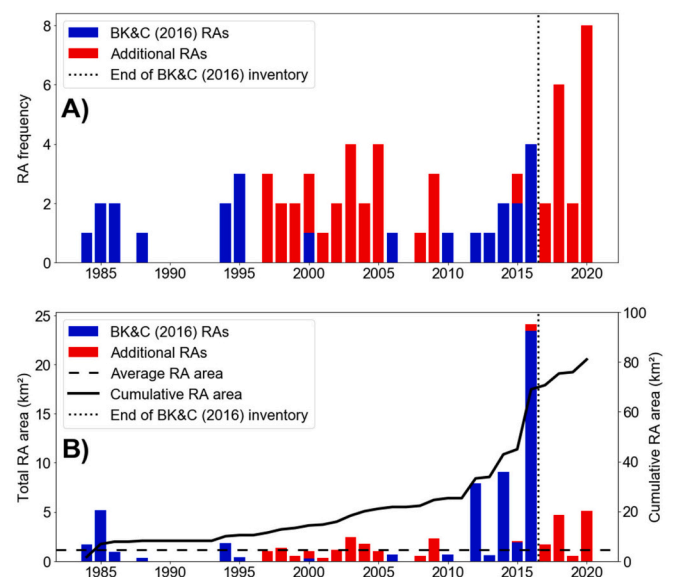


Fig. 1. A) Frequency of rock avalanches in Glacier Bay National Park & Preserve, Alaska, between 1984 and 2020, from the original Bessette-Kirton and Coe (Bessette-Kirton and Coe, 2016) database and the additional RAs found in this study. B) Total annual rock avalanche deposit area and cumulative total from 1984 to 2020. Average RA area (1.16) read from the Total RA area (km^2) axis.

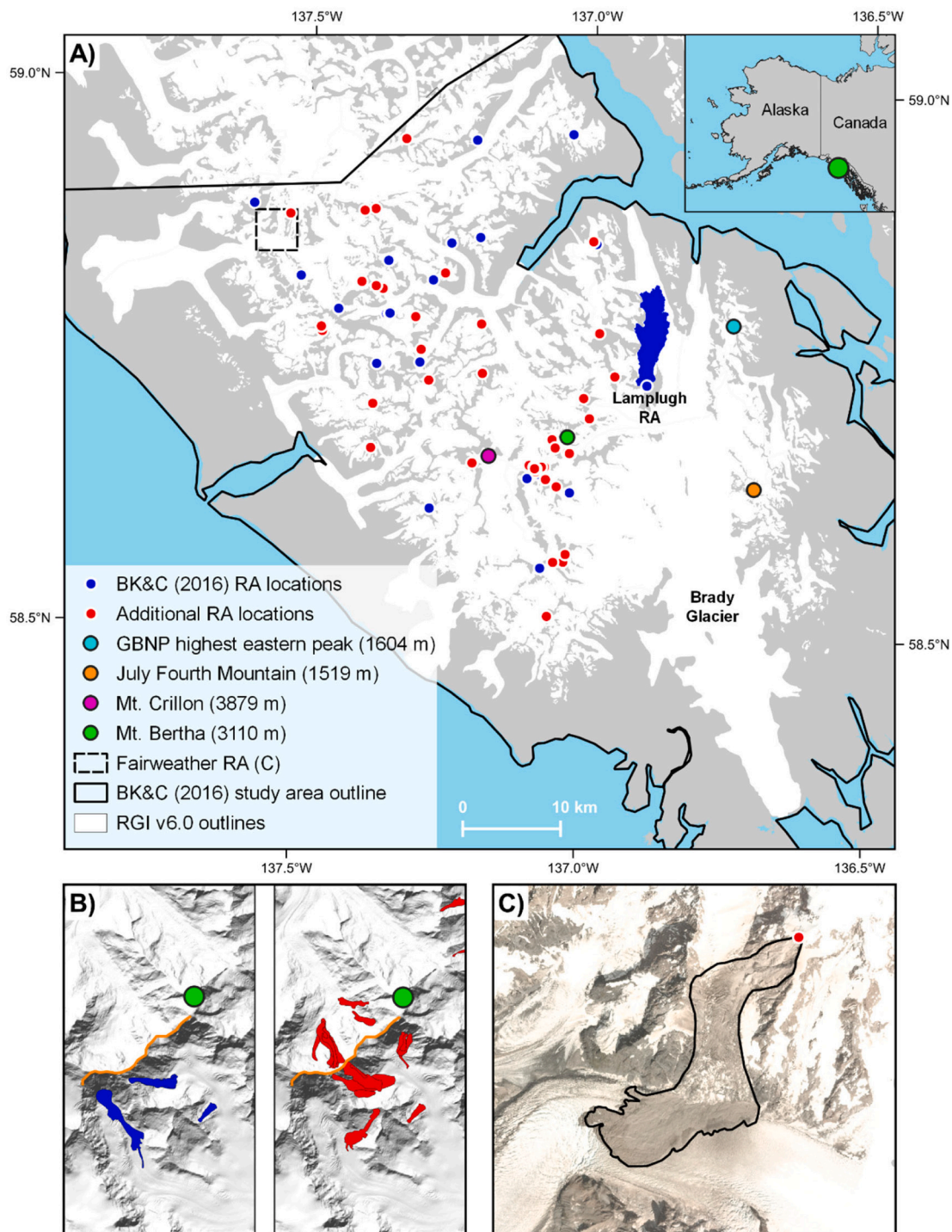


Fig. 2. A) Rock avalanche (RA) source locations for the Bessette-Kirton and Coe (Bessette-Kirton and Coe, 2016) database and the additional RAs found using GERALDINE. Lamplugh RA deposit (22 km²) shown in dark blue. The study area of Bessette-Kirton and Coe (2016) follows the coastline. B) Concentrated cluster of RAs around a ridgeline (orange line) between Mt. Bertha and Mt. Crillon identified by Bessette-Kirton and Coe (2016) (blue) and this study (red), and C) 2018 Fairweather Glacier RA image courtesy of Planet Labs Inc. (29-07-2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(a total of 2037 km²) at some point being covered by RA debris between 1984 and 2020. The largest previously unidentified RA we were able to identify within the Bessette-Kirton and Coe (2016) study period occurred in 2004 and had a deposit area of 1.5 km². The 27 additional RAs we found between 1984 and 2016 covered an average area of 0.49 ± 0.33 km², in comparison to the Bessette-Kirton and Coe (2016) RA inventory, which covered an average area of 2.29 ± 4.65 km² (Table 1).

Combining both datasets for 1984–2016 revises the average RA deposit size to 1.34 ± 3.29 km². Although the updated inventory indicates that RA frequency is consistent as opposed to clustered (Coe et al., 2018), the supply of debris is less uniform, with a significant ‘pulse’ of debris between 2012 and 2016. This is principally due to three large RAs: the 2012 Lituya, 2014 La Perouse, and 2016 Lamplugh RAs. The debris from these three events covered areas of 7.94 km², 5.45 km², and 22.19 km²

Table 1

Comparison summary statistics for the [Bessette-Kirton and Coe \(2016\)](#) RA inventory and the updated RA inventory presented here (this study).

	Number of RAs	Mean annual frequency	Total area (km ²)	Mean size (km ²) (± st. dev.)	Mean H/L (± st. dev.)
Bessette-Kirton and Coe (2016) (1984–2016)	24	0.73	54.98	2.29 ± 4.65	0.36 ± 0.13
This study (1984–2016)	27	0.82	13.33	0.49 ± 0.35	0.53 ± 0.16
This study (2017–2020)	18	4.5	11.99	0.67 ± 0.81	0.47 ± 0.11
All RAs (1984–2020)	69	1.86	80.29	1.16 ± 2.87	0.45 ± 0.15

respectively, totalling 44 % of all supraglacial RA deposit coverage. Areal coverage of all RA deposits from 2012 to 2016 accounted for 63 % of all RA deposit areal extents over the 33-year 1984–2016 period and 54 % between 1984 and 2020 ([Fig. 1B](#)). The largest single post-2016 event covered 3.4 km² of the Fairweather Glacier in the northwest of GLBA ([Fig. 1C](#)). Including the RA events of 2017–2020, overall average RA size decreases to 1.16 ± 2.9 km² ([Table 1](#)), due to 72 % of events 2017–2020 being <0.5 km². Although no exceptionally large events were identified that were comparable to the large RAs that occurred in 2012 (Lituya), 2014 (La Perouse), and 2016 (Lamplugh), each year from 2017 to 2020 (excluding 2019) experienced a RA larger than the mean RA size (1.16 km²). However, this indicates that 2016 marked the end of the period identified by [Coe et al. \(2018\)](#), where RAs >5 km² were increasing in frequency since 2012. None of the additional RAs in this study were > 5 km², and we have instead infilled the inventory with harder to detect ‘small’ (< 0.5 km²) events. In contrast to the 2012–2016 period, the years with the highest RA frequencies (2018 and 2020) are not characterised by the largest debris areal coverage due to a lack of large events.

The magnitude-frequency relationship for our updated RA inventory shows that a typical power-law relationship is not a robust fit for these data ([Fig. 3](#)). A *p*-value close to 1 indicates good power-law fit; however, our dataset produces a *p*-value of 0.323. Above RA sizes 3×10^6 m², the power-law relationship decays and underestimates RA area, whereas the cutoff value, where the inventory no longer follows the power-law

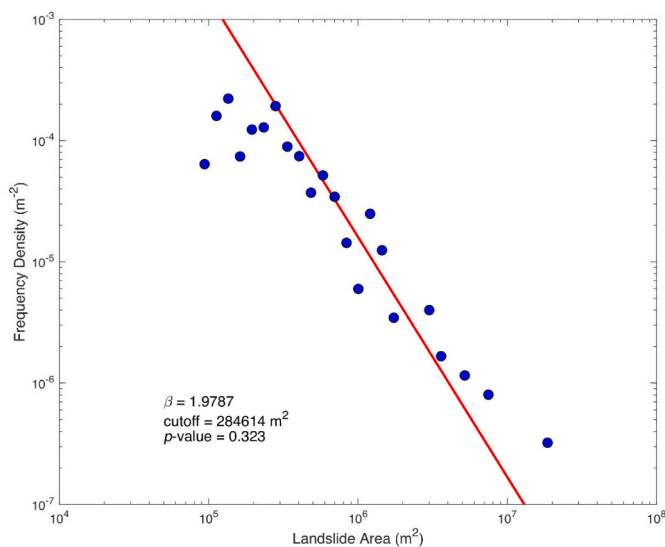


Fig. 3. Magnitude frequency relationship of rock avalanches identified in Glacier Bay National Park using a modified version of the method of [Tanyaş et al. \(2018\)](#).

relationship at the smaller RA sizes, is high at 284,614 m². A power-law relationship can therefore only describe a small subset of this new inventory. It must be noted that our power-law fit is, in effect, only attempting to span what we have classified as RA, which as a landslide process sits at the low frequency – high magnitude end of more complete event or historical inventories. The scaling exponent (β) of the ‘best’ power law fit to these data, which is used to show the dominance of either small-frequent or large-rare events is low (1.9787) in relative terms in comparison to other landslide databases ([Tanyaş et al., 2018](#)), indicating larger events are greater debris contributors than small events ([Hergarten, 2003](#)). This is primarily driven by the three large (> 5 km²) RA events that occurred during 2012–2016.

3.2. Spatial distribution

Our new inventory of 69 RA events that occurred between 1984 and 2020 in GLBA displays spatial clustering in the western half of the national park ([Fig. 2A](#)), where topography has greater relief ([Fig. S2](#)). This indicates that manual identification did not neglect any specific areas, because neither the original inventory nor the updated inventory presented here find RAs in the eastern region. Consistent with the dataset of [Bessette-Kirton and Coe \(2016\)](#) and the analysis by [Coe et al. \(2018\)](#), all additional RAs identified in this study are distributed around the modelled transition of permafrost likelihood, from ‘occurrence in all conditions’ to ‘only under favourable conditions’ ([Gruber, 2012](#)) ([Fig. 4A](#)). No RAs are deposited onto glaciers in the eastern region of GLBA around the Brady icefield ([Fig. 2A](#)): a region with permafrost only likely under very favourable conditions, or not at all ([Fig. 4A](#)). This correlates with RA source area maximum elevation, with most events initiated at elevations around ~2000–2500 m above sea level (a.s.l.) ([Fig. 4B](#)). Even the highest peaks of the eastern area do not reach these altitudes (all peaks <1604 m a.s.l.), perhaps providing a climatic/topographic threshold to RA occurrence. However, this eastern area is characterised by large areas of dirty ice and/or debris cover around the lateral edges of glaciers making identification with GERALDINE difficult due to the minimal contrast between new RA debris and existing supraglacial debris ([Smith et al., 2020](#)). In this case, the manual analysis of satellite images is more reliable, but still difficult ([Bessette-Kirton and Coe, 2016](#)).

In addition to RA association with the modelled permafrost boundary in GLBA, a spatial cluster of 16 previously undetected RAs were identified between Mt. Crillon (Lat: 58.662778, Long: -137.171944) and Mt. Bertha (Lat: 58.682028, Long: -137.039167) ([Figs. 2B and 5](#)) over the study period. This is in addition to the four already documented (two of which failed from the same source and were almost identical in terms of their runout extent at the mapping scale of [Fig. 2B](#)). This cluster represents ~29 % of all RA events, and 13 % of the area of RA deposits. The years 2003 and 2018 marked the most active years, with three RAs apiece ([Fig. 5A](#)). The 2003 events result from what appears to be the partial collapse of the southwestern ridge that runs between Mt. Crillon and Mt. Bertha, the deposits of which covered a combined area of 2.08 km². This ridge was the site of nine of the additionally identified events and two events documented by [Bessette-Kirton and Coe \(2016\)](#). The Geologic Map of Alaska ([Wilson et al., 2015](#)) indicates no unique lithologic/structural differences or any (known) fault lines that may cause this heightened activity, although we have not undertaken a detailed analyses of the topographic/geomorphic drivers and differences.

Aspect also appeared to be a controlling factor on the susceptibility of slopes to RAs, with 28 % of events occurring on north facing slopes (340–20°) ([Fig. 6A](#)) and 20 % occurring on south facing slopes (160–200°). Normalising RA slope aspect by all slope aspects in the study area ([Fig. S3](#)), shows that north facing slopes were still dominant with regards to failure, and east facing slopes (90–120°) featured a higher prevalence of events proportionally ([Fig. 6B](#)). No large events (> 3 km²) occurred on the dominant active slope aspects (north and south facing). These trends mirror those found by [Coe et al. \(2018\)](#) despite our

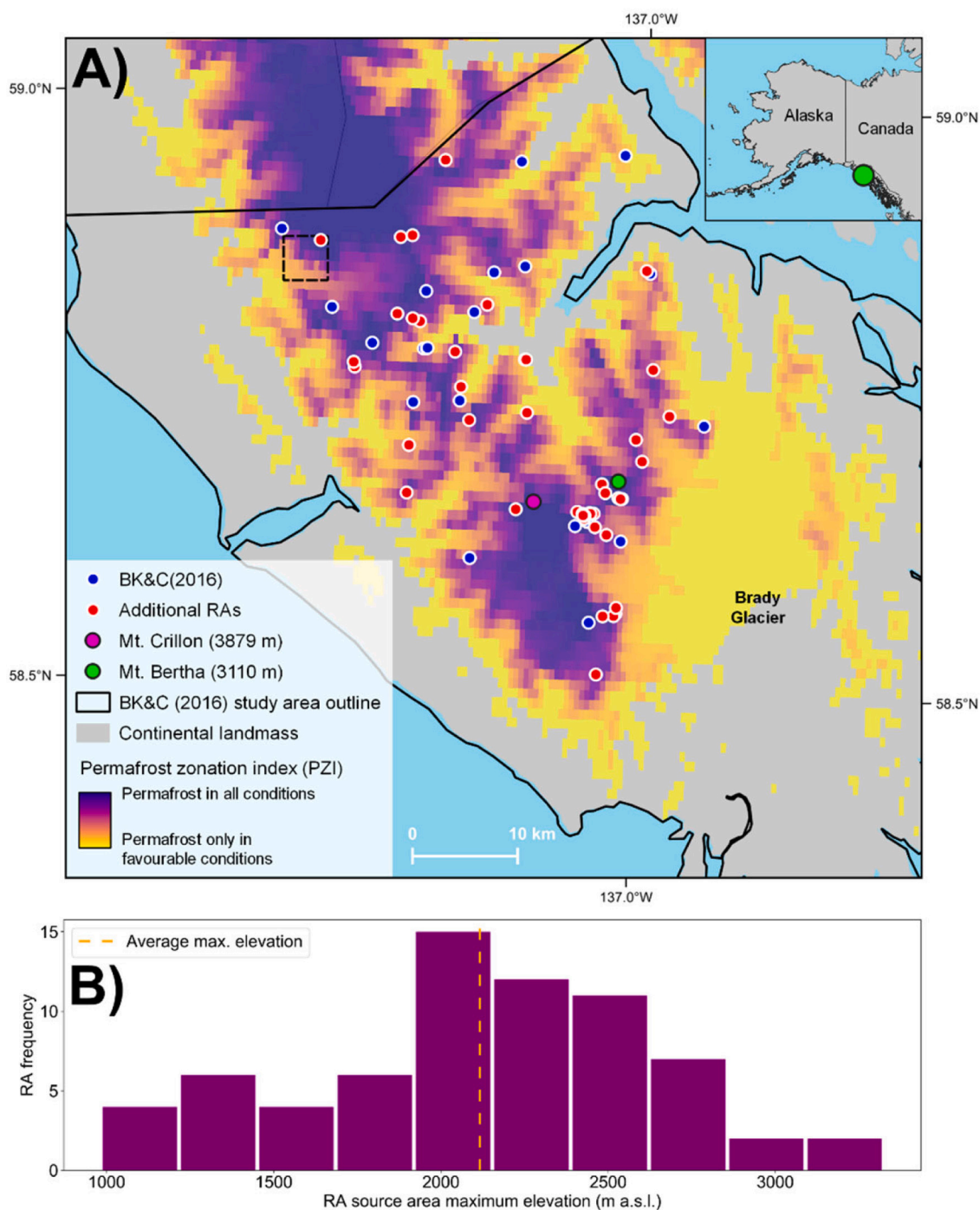


Fig. 4. A) RA locations from the Bessette-Kirton and Coe (Bessette-Kirton and Coe, 2016) database and the additional RAs identified in this study, in relation to the Permafrost Zonation Index (PZI) of Gruber (2012). The PZI is the likelihood of permafrost occurring in any given location. B) Histogram of RA source maximum elevations.

study increasing the number of identified events by 53 % over the same time frame. A similar aspect trend was also observed during the 2003 heatwave in the European Alps (Gruber et al., 2004).

3.3. RA sequestration

Of the 69 RAs found between 1984 and 2020, 58 % of RAs were sequestered into the ice within two years, 8 % were partially sequestered, and 20 % were not sequestered and remain on the surface. The remaining 14 % included RAs that occurred in 2020, so there has been insufficient time to determine whether they will be visible the following

year, and two RAs from 1984 and 1986 that we could not identify from the Bessette-Kirton and Coe (2016) dataset. Of these 2020 RAs, two (RA ID 66 and 67) are likely to stay visible due to partial/complete deposition below the snowline in their respective locations, while the remaining six were sequestered. Of the 27 additional RAs we found that were not identified in the original inventory, 21 were sequestered within two years.

3.4. Mobility

A key point raised by Coe et al. (2018) was the increase in RA

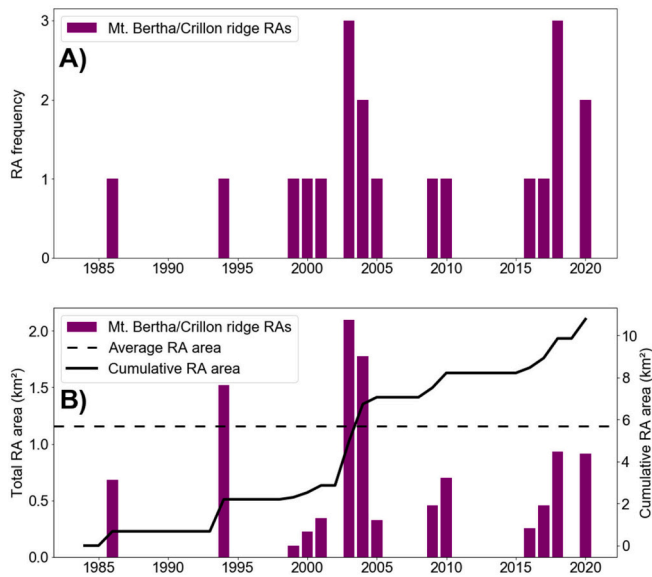


Fig. 5. Frequency (A) and area (B) of RAs occurring between Mt. Crillon and Mt. Bertha. Average RA area (1.16) for the complete RA inventory (all 69 events) read from the Total RA area (km²) axis.

mobility over time. RA mobility is calculated by dividing the total fall height of the RA (highest elevation of the source area and lowest elevation of the deposit), by the maximum runout distance of the RA (source to deposit terminus), which is referred to as H/L . This metric is a crude proxy for the friction angle/travel angle (Heim, 1932; Davies and McSaveney, 2013; Sosio et al., 2012), with 0.6 a common threshold applied for rock avalanche like motion. Using the updated inventory, we calculated H/L (Fig. 7) and found no significant upward trend ($p = 0.66$ using the Mann-Kendall test) in RA mobility over the 1984–2020 time period, four years longer than the original Besette-Kirton and Coe (2016) inventory. Our new inventory has a mean H/L value of 0.45, compared to 0.36 estimated by Coe et al. (2018) (Table 1). We attribute

this to the identification of several smaller RAs, decreasing average RA size from 2.29 ± 4.65 km² to 1.16 ± 2.9 km² (Table 1). Smaller RAs are well known to have higher H/L values than larger events (Sosio et al., 2012; Aaron and McDougall, 2019), although this relationship is complex (Evans and Delaney, 2015). RA mobility is less than previously believed in the region and lower than other databases of glacial RAs. Deline et al. (2014) gathered data from 56 supraglacially deposited RAs worldwide and found an average H/L of 0.28, whereas Besette-Kirton and Coe (2020) identified 220 RAs in the St. Elias Mountains of Alaska, and found an average H/L of 0.37. The GLBA average is more comparable to that of Besette-Kirton and Coe (2020). This is because they did not exclude events due to a size/mass threshold, with an average RA size of just 0.6 km², whereas the database of Deline et al. (2014) is made up of RAs with volumes $>10^6$ m³. However, the derivation of volume from area is poorly constrained with few quantitative examples to account for the complex patterns of erosion, entrainment and compaction that preclude simple source zone differencing (Besette-Kirton et al., 2018), from which the Deline et al. (2014) inventory predominantly relies

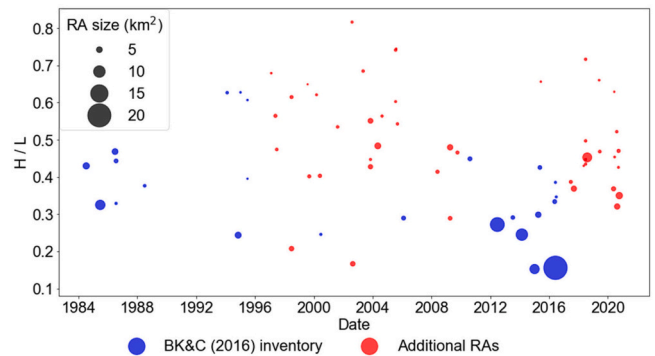


Fig. 7. Ratio of fall height (H) to travel distance length (L) for all rock avalanches (RA) identified by Besette-Kirton and Coe (Besette-Kirton and Coe, 2016) and the additional RAs identified in this study, in Glacier Bay National Park during 1984–2020. Marker size represents RA size.

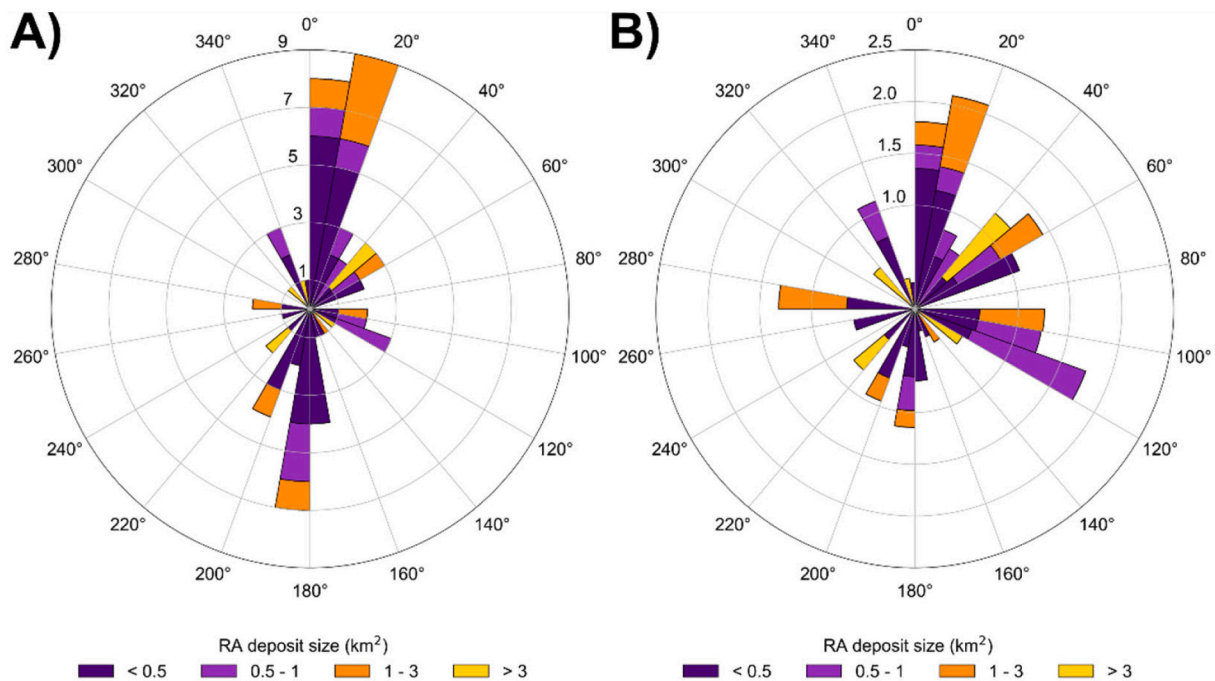


Fig. 6. A) Frequency of rock avalanche source area aspects categorised into 20° bins (see Table S2 for bin statistics), B) Rock avalanche area aspects normalised using all slope aspects in Glacier Bay National Park.

upon.

3.5. Potential causes of rock avalanche occurrence

Coe et al. (2018) proposed increasing atmospheric temperatures and subsequent rock-permafrost degradation as the likely cause of increasing RA size in the study area. However, they acknowledged that the exact processes that cause degradation and destabilisation are unknown, and the slopes are likely pre-conditioned through accumulating elastic crustal strain, glacial thinning, and increased precipitation. With the addition of 45 RAs to the existing inventory, our results are also spatially coincident with the modelled boundary/transition of permafrost favourability (in the period 1961–1990) created by Gruber (2012) (Fig. 4A). However, the permafrost zonation index (PZI) of Gruber (2012) is a global dataset with necessary simplifications and higher resolution permafrost models/data would offer a considerable advance in further quantifying any links between permafrost and RA events. Future improvements to local or global permafrost products will allow the RA dataset presented here to be reanalysed.

To look at possible air temperature controls we use the higher resolution ERA5-Land reanalysis, 2-m height, monthly product, temperature data (Muñoz-Sabater, 2019) (Figs. 8 and 9). Mean monthly temperatures across ERA5 cells in GLBA and RA monthly frequency (Fig. 9) show a strong seasonal control on occurrence. RA derivation from 37 years of data using GERALDINE gives us confidence that this is

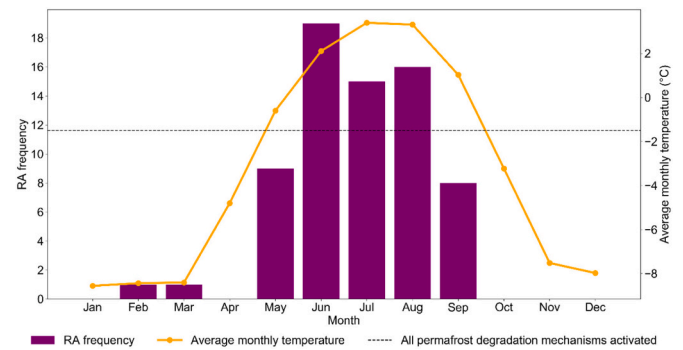


Fig. 9. Monthly rock avalanche frequency (assigned as the image month in which the RA is first visible) and average monthly temperature from ERA5-Land temperature data using the cells in which RAs occurred within, in Glacier Bay National Park & Preserve during 1984–2020.

real rather than a seasonal detection bias, however, Landsat image frequency in November, December, and January is notably lower (Fig. S1B), and this may play a role in preventing some RA identification during these months. However, our confidence in this seasonality is high because we evaluated 37 years of data on an annual basis using a debris biased approach (GERALDINE). All but two RAs were first visible in imagery between May and September when average monthly

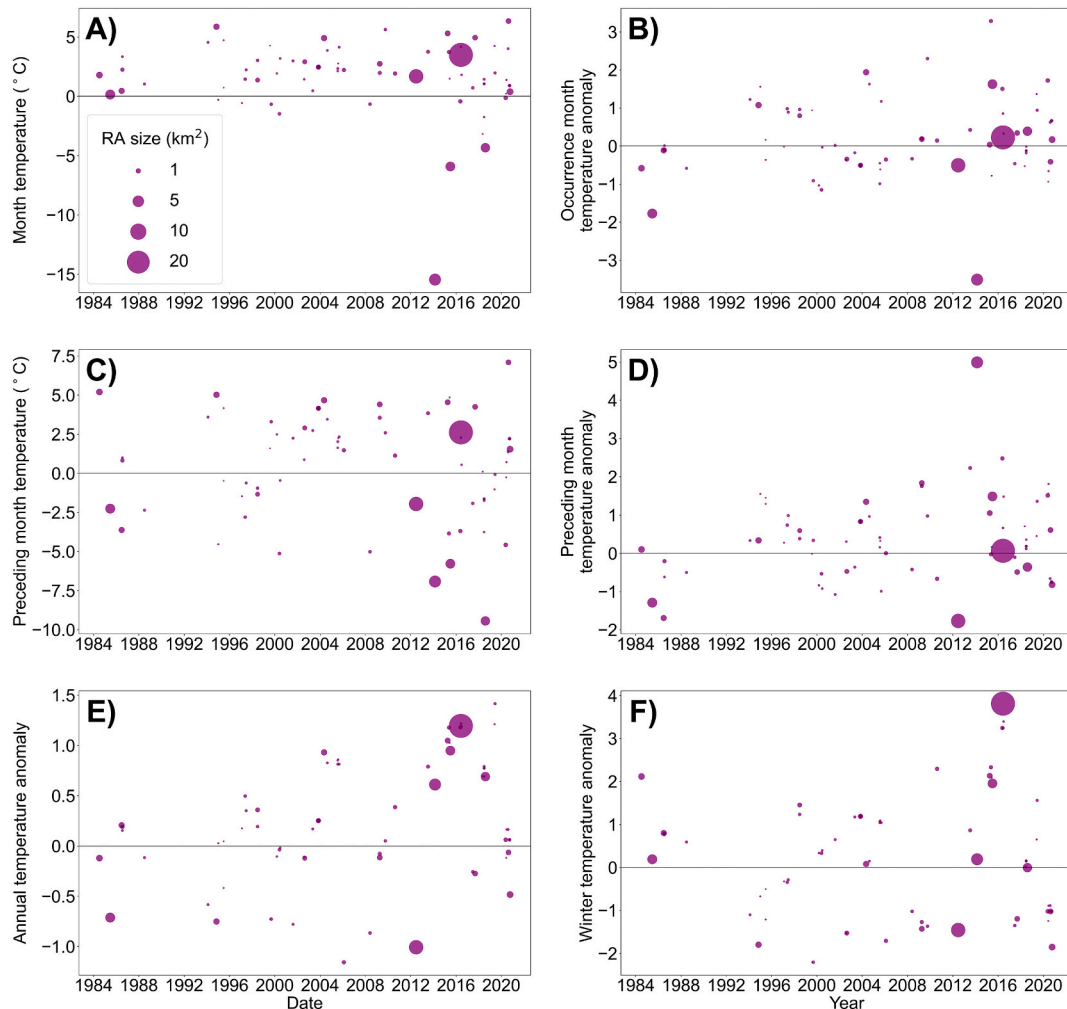


Fig. 8. ERA5-Land temperatures for each rock avalanche A) month of occurrence temperature, B) month of occurrence temperature anomaly, C) preceding month of occurrence temperature, D) preceding month of occurrence temperature anomaly, E) annual temperature anomaly, and, F) winter (December, January, February) temperature anomaly.

temperatures are consistently above -1.5°C . This seasonality in RA occurrence has been found in other areas of Alaska (Bessette-Kirton and Coe, 2020) and the addition of our 45 (albeit often smaller) RAs shows that this seasonality of triggering is not size or detection biased. The two RAs identified outside of the May–September period, the La Perouse RA (February 2014) and the Orville-Wilbur RA (March 2015), have not previously been assigned a trigger (Coe et al., 2018; Hibert et al., 2019). In terms of absolutes, RAs between 1984 and 2020 are being detected in months with GLBA average temperatures between $\sim -4^{\circ}\text{C}$ and $+3^{\circ}\text{C}$. We can improve the granularity somewhat using the ERA5 cells (22) covering GLBA assigned to each RA source zone and the temperature anomalies (Fig. 8). Only 12 RAs occurred during a month with an average temperature below 0°C (Fig. 8A), and only five occurred during a month with an average temperature below -1.5°C ; the temperature at which all rock-permafrost degradation mechanisms are active, as outlined in the introduction. However, 2 m air-surface temperature is not rock surface temperature, especially where aspect strongly controls solar radiation receipt (e.g., Lamp et al., 2017). Rock surface and air temperature are also not representative of temperatures at the depths that RA shear planes may be located. However, RAs on north-facing slopes dominate our inventory (Fig. 5A), and their dominant temperature control is air temperature (e.g., Salzmann et al., 2007; Noetzli et al., 2007; Noetzli and Gruber, 2009). Deep seated RA shear planes likely respond to longer term warming rather than shallow permafrost thaw, but, recent work has shown correspondence between degrading permafrost (and precipitation) and both the onset, and, deformation rate of rock-slope failures in Norway (Hilger et al., 2021). In comparison to the monthly average temperature in which RAs were identified, 28 RAs experienced temperatures below 0°C in the month preceding failure (Fig. 8C). Of these 28 RAs, 18 occurred during a month with an average temperature $> 0^{\circ}\text{C}$, directly following a month during which the average temperature was $< 0^{\circ}\text{C}$, indicating a temperature rise through the temperature zone of maximum permafrost rock-slope destabilisation. Temperature anomalies for both RA occurrence month (Fig. 8B) and preceding month (Fig. 8D), show no clear association with failure, indicating the temperature of the month of failure is the key factor.

Calculated annual temperature anomalies for each RA show no clear relationship with RA occurrence (Fig. 8E), with an average anomaly of 0.244. Similarly, winter (December–February) temperature anomalies are also not a clear indicator of RA occurrence, averaging 0.198 (Fig. 8F). We do not rule out temperature anomalies at any time of year as a trigger for RAs, as it is highly likely that above average temperatures trigger RAs, as found elsewhere (e.g., the European Alps; Gruber et al., 2004), but they cannot explain all RAs in the GLBA inventory.

On a larger scale, the Pacific Decadal Oscillation (PDO) and El-Niño-Southern Oscillation (ENSO) have a strong influence on temperature and precipitation in Alaska (Fleming and Whitfield, 2010; Wendler et al., 2017), switching from positive (warmer and wetter) to negative (cooler and drier) phases (Papineau, 2001; Fleming and Whitfield, 2010). Switches to positive PDO and ENSO phases have been attributed to recent increases in glacier mass loss and thinning in Alaska (Jakob et al., 2021; Hugonnet et al., 2021). We utilised the PDO index data from NOAA (2021) and the Multivariate El-Niño-Southern Oscillation (MEI) data (Wolter and Timlin, 2011) to assess RA relationship with these large-scale climatic influences. Although increased temperatures and subsequent glacier thinning are both known to cause increased rock slope activity (Deline et al., 2014), in accordance with the analysis of Coe et al. (2018), we determined no correlation between RA occurrence and PDO and ENSO behaviour (Fig. S4).

We rule out earthquakes as a cause of RAs because only one $>M 4.0$ earthquake occurred in the region that: (i) corresponded to a RA window of occurrence (RA ID 30), and (ii) occurred within the landslide trigger zone. This was an $M 5.6$ earthquake on 27/05/1999, which should have a landslide trigger zone of $\sim 400\text{ km}^2$, according to the relationship between area affected by landslides and earthquake magnitudes (Keefer, 1984, 2002). Although we rule out earthquakes as a dominant triggering

mechanism, the study area experienced 14 earthquakes $>M 4.0$ over the study period (1984–2020). The area is also undergoing high rates of post-glacial isostatic uplift at $\sim 24\text{ mm y}^{-1}$, due to the loss of over 3030 km^3 of ice in the past 300 years (Larsen et al., 2005). Seismicity and redistribution of rock slope stress therefore remain likely contributing pre-conditioning factors for slope instabilities (Ballantyne, 2002).

4. Discussion

4.1. Why is GERALDINE detection better?

The manual analysis method of Bessette-Kirton and Coe (2016), which involved selecting a minimum of one cloud-free Landsat image acquired annually between May and October and visually analysing it for RA deposits using different band combinations (104 images analysed in total) has long been considered the most reliable approach, and we chose the inventory for additional evaluation due to its high quality. We have shown that this was outperformed by GERALDINE. GERALDINE outputs target likely deposits for manual validation, which allowed the detection of several smaller RA deposits in GLBA over the same time period (1984–2016) as the Bessette-Kirton and Coe (2016) inventory, with the average deposit size of additional RAs being 0.49 km^2 , in comparison to the average RA deposit size (2.29 km^2) of the original inventory (Table 1). We suggest the smaller area additional detections identified from GERALDINE are because larger deposits are easier to detect both visually and using seismic methods (Ekström and Stark, 2013). We further investigate the under-reporting of RAs in the Bessette-Kirton and Coe (2016) inventory by comparing the minimum elevation of RA deposits to look at sequestration/spatial bias (Fig. 10). The Bessette-Kirton and Coe (2016) inventory did not detect RAs that occurred at all elevation bands, and above 1600 m a.s.l. , only one small RA deposit (deposit ID 24 at 0.7 km^2) was identified in the original inventory, whereas we identified 14 additional RA deposits (Fig. 10). This under-reporting at higher elevations is likely due to the difficulties of detection when RAs are deposited into glacier accumulation zones where they are visible for a shorter period of time / appear in less images. This is due to a higher likelihood of precipitation falling as snow (and wind redistribution of this snow), and subsequent sequestration into the ice and englacial transport system. In contrast, deposition of RA material at lower elevations in glacier ablation zones ensures they are visible on the surface for longer, and likely annually for many years, aiding manual detection. However, we also found four additional RAs detected below the ELA of the largest glacier in GLBA: Brady Glacier ($\sim 745\text{ m a.s.l}$ in 2013; Peltó et al., 2013) (Fig. 10). Three of these deposits were deposited onto the John Hopkins Glacier, two of which (deposits ID 32 and ID 47) were deposited onto a branch flowing at $\sim 800\text{ m a.s.l.}$, and the remaining (deposit ID 50) deposited onto a branch with a velocity of

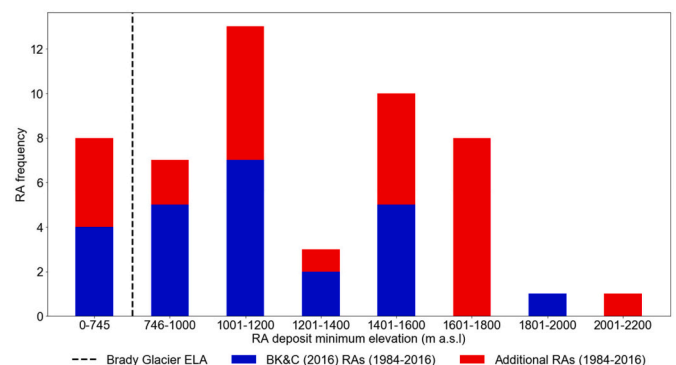


Fig. 10. Minimum elevation of all rock avalanche deposits identified by Bessette-Kirton and Coe (2016) and the additional RAs identified in this study, that occurred between 1984 and 2016, in relation to the Brady Glacier equilibrium line altitude (ELA) identified by Peltó et al. (2013).

~350 m a⁻¹. These fast velocities cause rapid modification of 'diagnostic' RA deposit characteristics, and rapid incorporation into medial and lateral moraines, making manual detection difficult, particularly from the limited cloud-free imagery in GLBA as per [Bessette-Kirton and Coe \(2016\)](#). The remaining RA deposit occurred in a steep narrow valley, where it could easily be mistaken as a bare rock slope on a 2D Landsat image. An added benefit of GERALDINE is that it allows for the rapid analysis of many more images than are practical using manual methods (greater than an order of magnitude more in this case). This situation likely resulted in additional detections compared to the original study.

The results of this study prove GERALDINE is a valuable tool for RA detection, particularly in areas where debris cover is more intermittent (due to the detection challenges posed by debris deposition onto already debris covered glaciers; see [Smith et al. \(2020\)](#)). We recommend it is applied alongside other detection tools, such as seismic inversion ([Ekström and Stark, 2013](#)), in other high mountain glaciated regions, particularly the 'bellwether' sites identified by ([Coe, 2020](#)), to allow investigation of spatial and temporal trends in RA occurrence on a global scale, with GERALDINE able to work backwards within the long timeseries of Landsat imagery.

4.2. Temporal, spatial and areal RA trends

Our new inventory has filled in many of the years in which no RA activity was previously documented, showing RAs in GLBA are a more chronic / consistent supplier of debris and do not cluster temporally ([Coe et al., 2018](#)). RAs are responsible for a 'background' rate of debris delivery onto glaciers in GLBA, with a 'spike' in debris delivery during years of exceptionally large RAs that input a disproportionately high amount of debris into the glacial domain and dominate the historical inventory, in the 2012–2016 period. This background consistent supply of debris through rock-slope failures in GLBA has not previously been recognised ([Coe et al., 2018](#)) but has been found elsewhere over a longer time period (1950–2008) and a larger study area (~25,000 km²) in the Chugach Mountains, Alaska ([Uhlmann et al., 2013](#)). Similarly, in the St. Elias Mountains, RA frequency is constant and considerably higher than we find in GLBA (6 RAs per year as opposed to 1.9 per year in this study) over a smaller study area (3700 km²) ([Bessette-Kirton and Coe, 2020](#)). However, RAs >5 km² were not documented in the St. Elias Mountains, and only three were documented in the Chugach Mountains, indicating the three that occurred in GLBA in just 4 years represent an exceptional period of large debris supply. In addition to the three large RAs we document between 2012 and 2016 in GLBA, on the 17/09/2022 another large RA (7.17 km² deposit area) was deposited onto the Lamplugh glacier, and partially ran out over the 2016 Lamplugh RA deposit ([Petley, 2022](#)). We know of no other glacial areas worldwide with such a high documented prevalence of large RAs over the last 40 years. We find the highest RA frequencies between Mt. Crillon and Mt. Bertha in GLBA, which experienced 29 % of all RAs recorded ([Fig. 5](#)). Likewise, [Bessette-Kirton and Coe \(2020\)](#) documented that >50 % of the RAs occurring in the St. Elias mountains initiated from source areas that failed repeatedly. This was attributed to lithology and tectonic setting ([Bessette-Kirton and Coe, 2020](#)). However, the extreme topography in these regions, rising from sea level to >4000 m a.s.l. within 25 km, is characterised by numerous peaks and ridges, which are particularly susceptible to permafrost degradation as the warming can penetrate from multiple sides ([Noetzli et al., 2007](#)). Each area experiencing multiple failures over multiple years likely has a unique cause, but set within regional and global drivers of change that may be moving slopes towards their ultimate thresholds. It is unknown what combinations of conditions causes these areas to 'switch on,' and, once that (in)stability threshold has been crossed, if they will ever 'switch off' due to, for example, exhaustion or self-stabilisation of their sources, as has been hypothesised in paraglacial environments ([Ballantyne, 2002](#)). For the Bertha-Crillon ridge ([Figs. 2B and 5](#)) two clusters, 1999–2005 and 2016–2020 qualitatively appear to show a ramping up of event frequency-area. RA frequency in GLBA as a

whole shows no clear signal of change when we include our detections alongside the previous inventory ([Figs. 1 and 7](#)). The three large RAs between 2012 and 2016 were exceptional in areal extent, and perhaps mobility (which is linked to volume). These large events disproportionately impact long-term debris area patterns ([Fig. 1B](#)), although a number of smaller events also exhibited similar mobility ([Fig. 7](#)). These large events are superimposed on a possible upward trend in debris coverage, after the three large events it is the frequency of moderate size events that drive this trend.

Our new inventory is unique in that it is derived from all available Landsat data, ensuring a level of completeness not previously available, and in the case of GLBA, the inventory is not affected by earthquake-triggered RAs, therefore, it represents the best currently available assessment of the background rates of RAs onto glaciers – with the caveat that past earthquakes will have affected rock-slope stability long-term. By utilising this more complete inventory we analysed the magnitude-frequency relationship ([Fig. 3](#)) in which a weak power-law fit is observed – we cannot statistically say these data are best described by a power law. As is the case with most inventories, there is a point at which smaller event sizes deviate ('roll over') from the power-law (for full review, see [Tebbens, 2020](#)), yet we also see this occurring at larger sizes as a 'roll under'; they are more common than the power law fit suggests. We attribute this deviation at larger event sizes to the increased mobility (and subsequently areal coverage via spreading) of glacially deposited RAs in comparison to their non-glacial counterparts for a given volume ([Sosio et al., 2012](#)). It has also been found that using data collected over time to derive frequency-area relationships can be problematic, particularly if large landslide frequencies have increased, shifting the distribution tail upwards ([Schlögel et al., 2011](#)). Deviations at smaller event sizes are frequently attributed to smaller events going undetected ([Tebbens, 2020](#)), and we cannot detect events <0.05 km² due to method limitations ([Smith et al., 2020](#)). However, the causes of this rollover point are debated and recent research indicates that it may be accurate due to the change in physical processes occurring at small and large scales, due to variations such as lithology ([Tebbens, 2020](#)). In GLBA, small (<0.5 km²) events are likely short runout, low spread, rock topples and rock falls, producing no homogenous deposit on the ice surface. We have witnessed events that leave a small, thin dust covering on the ice surface more akin to a debris fan, with snow/ice still universally visible beneath due to their minimal thickness. However, we do not categorise these as RAs, as their appearance and mobility are dramatically different from a RA deposit, and therefore we exclude them from the inventory. Size bias is also affected by image frequency. It is not possible to identify whether large failures are in fact a collection of smaller failures. [Dufresne et al. \(2019\)](#) showed using seismic records that the largest RA in GLBA, the 2016 Lamplugh RA, was two discrete events separated by 2 h (21 km² and 3.4 km² extents).

4.3. Warming triggers

We cannot conclusively show RAs in GLBA are triggered by a rise in atmospheric temperature and subsequent rock-permafrost degradation, but it is likely a contributing factor over a range of timescales. The dominant seasonal trend (May–September) of RA occurrence in GLBA, also found farther north in the St. Elias Mountains ([Bessette-Kirton and Coe, 2020](#)), coupled with the average temperatures of these months, rising atmospheric temperatures in the region as a whole, and a close association with the modelled boundary/transition of permafrost favourability ([Gruber, 2012](#)), indicate temperature-related destabilisation mechanisms are likely key for RA generation in GLBA. As previously noted by [Coe et al. \(2018\)](#), the exceptionally large RAs in 2012, 2014, and 2016, all took place during a multi-year period of record-breaking warm winter and spring temperatures. The seasonal triggering temperatures for our RA inventory ([Figs. 8 and 9](#)) are within the destabilisation temperatures (> -4 °C, with the strongest effects as 0 °C is approached) modelled by [Mamot et al. \(2021\)](#), although the authors caveat that

transferability is strongest for slopes similar to the model setup. The Gruber (2012) permafrost model output we use is a low-resolution product, which does not take into account slope aspect nor the topographic nuances that determine permafrost on steep, mountain slopes (e.g. Etzelmüller et al., 2022). In addition, it was created using mean annual air temperature data from 1961 to 1990, so, it represents an outdated, probably over-estimated permafrost extent, and is only directly applicable to RAs that occurred between 1984 and 1990 in our inventory. There is a pressing need for a high-resolution permafrost map in the area, to help discern the role permafrost degradation on RA preparation and/or triggering, and to assess the role of shallow warming in the onset of deeper seated RA failures.

Despite the limitations of the Gruber (2012) permafrost zonation product, the dominance of north-facing slopes as RA source areas in GLBA further supports permafrost degradation mechanisms. North facing slopes experience much less inter-annual temperature variability and subsequent permafrost thaw depth than their south-facing counterparts, due to their limited exposure to shortwave radiation (Gruber et al., 2004). Current warming is amplifying these temperature variations and modelled future warming indicates further increased sensitivity (Salzmänn et al., 2007; Noetzli et al., 2007). This is because north-facing slopes will be subject to stronger shortwave radiation during summer months, increasing their susceptibility to ground-surface temperature changes, increasing thaw depth and subsequent chance of failure (Salzmänn et al., 2007; Noetzli et al., 2007). A similar trend of high rockfall incidence at the continuous/discontinuous permafrost boundary has been found in other high mountain areas, e.g., New Zealand and European Alps (Allen et al., 2011; Fischer et al., 2012). This is consistent with the hypothesis that rock-permafrost degradation is the most likely cause of rock slope failures in the region (Coe et al., 2018). The predicted increases in atmospheric temperatures over the coming century and subsequent increased permafrost degradation (IPCC, 2019) is expected to weaken slope stability further in GLBA, consequently increasing the size and frequency of RA events.

4.4. Glacial sediment budgets and extra-glacial impacts

The 53 % RA number and 19 % RA deposit area underestimation in GLBA, an area where RA activity is well documented, raises questions regarding the completeness of other RA inventories such as those of Uhlmann et al. (2013) and Besette-Kirton and Coe (2020). If these existing glacial RA inventories, created using manual analysis of satellite imagery, also underestimate RA frequency by over 50 % and RA area by ~20 %, as found in this study, rates of debris supply onto/into glaciers from RAs are likely much higher than previously quantified. If this pattern holds true for other similarly active, high elevation glacial environments with (currently) known RA clusters, for example New Zealand's Southern Alps, parts of the Himalaya, Tien Shan, and Pamir, it would result in significant global underestimates of glacial sediment fluxes from subaerial mass movements. Given that we quantify ~60 % of subaerial supraglacial RAs emplaced above the ELA, much of the sediment flux from RAs will, on deposition/removal from the glacier transport system, be considered part of the glacial sediment flux. Uhlmann et al. (2013) noted the (extreme) sediment yields at Alaskan glacial snouts were an order of magnitude below their quantified longer-term subaerial landslide fluxes; our data indicate that a portion of this 'glacial' debris originates from frequent supraglacial landslide additions travelling englacially. Separating out the contribution of subaerial RA to both supraglacial and englacial environments, and establishing if the original RA provenance can be deduced from englacial and emergent debris are key outstanding research challenges. Prior to this, more robust area-volume scaling relationships would be beneficial to move from what can be quantified in 2D imagery to volumetric fluxes.

The fate of this under-estimated debris is also unknown. If high rates of RA sequestration are also found elsewhere in Alaska and in other glaciated regions, we question how much debris is locked up in glaciers

and how this will affect proglacial and extraglacial environments in the future. Many large Alaskan glaciers discharge into the ocean, and glacial debris is known to be rich in bioavailable iron (Hawkins et al., 2018). The export of glacial debris to the oceans can have fertilising effects (Raiswell et al., 2008, 2016; Hawkins et al., 2014), so the subaerial glacial contribution to the iron-limited Gulf of Alaska (e.g., Coyle et al., 2019) may be greater than previously believed.

5. Conclusion

Our review of an existing glacial rock avalanche (RA) inventory in Glacier Bay National Park & Preserve, Alaska, between 1984 and 2016, with a new semi-automatic detection method (GERALDINE), provides evidence of a large (53 %) underestimation of the number of glacial RAs and RA area (19 %). Of those that were missed, the majority were small RAs that occurred across all elevation bands. RAs did not cluster temporally, as indicated by the previous inventory (Besette-Kirton and Coe, 2016); instead over the 37-year period we investigated (1984–2020), a background rate of debris was delivered by RAs. This debris delivery did, however, increase substantially between 2012 and 2016, due to three large (> 5 km²) RAs before returning to pre-2012 levels. Despite GERALDINE allowing the detection of numerous smaller events, these three large events between 2012 and 2016 remained the greatest debris contributors, contributing 44 % of overall debris areal extent. The new inventory identified spatial clustering in the study area, with one ridgeline producing 29 % of all 69 RAs identified. Additionally, slope aspect played a key role in RA occurrence, with 28 % of events occurring on north-facing slopes (340–20°).

In contrast to previous analysis, we find no evidence for an increase in RA mobility over the study period and attribute this to our ability to detect smaller events. Analysis of RA triggering mechanisms indicates rock-permafrost degradation and temperature change to be the key drivers of these slope failures, with close association between the fringes of permafrost favourability and RA source location. In addition, the seasonality of RA occurrence is predominantly limited to the months of May – September. The only months where atmospheric temperatures are above the limit at which most rock-permafrost degradation-induced slope instabilities can be expected within and near the active-layer of the permafrost. The fate of all RA debris is quantified with 58 % of deposits sequestered within two years, and 8 % partially entrained and sequestered, providing the first estimate of RA sequestration rates on glaciers. This has important implications for glacial sedimentary budgets, which may be globally underestimated in areas with highly active slope processes. Here we have corrected what appears to be an areal bias in manual detections by using an automated tool, GERALDINE. This tool is a valuable resource to aid and update our understanding of glacial RAs, their magnitude and frequencies, links to climatic drivers, and their contribution to glacial sediment fluxes past, present, and future. Our updated and expanded inventory showcases how an area known for its high glacial RA activity is even more active than previously realised. It is important to quantify whether this activity is unique to the region, or whether other glacial areas across the world experience similarly high rates of debris delivery from large slope-failures.

Funding

Funding was provided by a Newcastle University Research Excellence Scholarship to WDS.

Code availability

doi:<https://doi.org/10.5281/zenodo.3524414>

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The code used to generate is hosted Open Access on Zenodo <https://doi.org/10.5281/zenodo.3524414>

Acknowledgements

This work was funded by a Newcastle University Research Excellence Award Ph.D. scholarship to W. Smith. Hillshade IFSAR digital terrain model used for elevation extraction were collected as part of the Alaska Mapping Initiative (USGS, 2018) and are available through the USGS EarthExplorer data portal. We thank Katherine Barnhart, Janet Carter, Brian Shiro (USGS), and Simon Allen (University of Zurich) for their constructive reviews. We thank ECMWF for the use of the ECMWF ERA5-Land dataset, and NOAA for the PDO data. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.geomorph.2023.108591>.

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