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Kill dates from re-exposed black mosses constrain past glacier advances in the northern Antarctic Peninsula

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ABSTRACT

Glaciers are receding in the northern Antarctic Peninsula and exposing previously entombed soils and plants. We used 39 black (dead) mosses collected from rapidly retreating ice margins at four sites along the Antarctic Peninsula to determine the kill dates using radiocarbon measurements and to constrain the timing of past glacier advances over the last 1500 yr. We established strict new criteria for sample collection to promote robust estimates of plant death. We found distinct phases of ice advance during ca. 1300, 800, and 200 calibrated years before 1950 (cal yr B.P.). We report estimates of the rate of glacier advance at ca. 800 cal yr B.P. at Gamage and Bonaparte Points (southern Anvers Island) of 2.0 and 0.3 m/yr, respectively. Although the range of kill dates is relatively narrow within a region, suggesting multiple glaciers advanced simultaneously, the rates of local advances can vary by almost an order of magnitude and are much less than retreat rates. Our kill dates coincide with evidence for glacier advances from other studies in the northern Antarctic Peninsula at ca. 1300, 800, and 200 cal yr B.P. and for penguin colony abandonment at several sites in the region ranging from 450 to 0 cal yr B.P. The combination of our new terrestrial evidence for glacier advances with other lines of evidence shows the regional synchroneity of glacial dynamics and cryosphere-biosphere connections during rapid climate shifts and the sensitivity of terrestrial ecosystems to climate cooling.

INTRODUCTION

The terrestrial cryosphere and biosphere of the Antarctic Peninsula are rapidly changing (Cannone et al., 2016; Cook et al., 2016; Amesbury et al., 2017; Silva et al., 2020), driven by atmospheric warming (Vaughan et al., 2003; Turner et al., 2005; Nicolas and Bromwich, 2014). Constraints on the timing of past glacier advances and retreats can provide context for understanding today's cryosphere and sensitivity to climate change (Davies et al., 2014), yet there are few records from terrestrial archives with which to estimate the timing of glacier behavior (Bentley et al., 2009; Simms et al., 2012, 2021).

Melting of glaciers worldwide affects sea level, water resources, and ecosystem processes and reveals previously entombed landscapes. In the northern Antarctic Peninsula, radiocarbon (^{14}C) dating of black (dead) mosses (Hall, 2007; Hall et al., 2010; Yu et al., 2016; Guglielmin et al., 2016), penguin remains and prey (e.g., Emslie, 1995), and ^{10}Be dating of glacier erratics (Kaplan et al., 2020) are among the few terrestrial records that provide evidence for the timing of increasing perennial snow and/or advancing glaciers in the past. Of the materials that can be dated, Smith (1982) and Fenton (1982) recognized the implications of re-exposed vegetation uncovered since the deglaciation of an ice cliff (Marr Ice Piedmont) behind the U.S. Antarctic research base Palmer Station (Anvers Island). The ^{14}C date of black moss signifies the moss kill age or close minimum age of glacier advances (and perennial snow and then ice accumulation) and entombment of the mosses, hereafter referred to as "kill dates" (Yu et al., 2016).

We know glaciers in the Antarctic Peninsula can respond rapidly to increased summer surface air temperatures (Cook et al., 2005), and in the northeastern Antarctic Peninsula, when modeled at centennial scales, glacier expansion resulted from cooling temperatures rather than increased precipitation (Davies et al., 2014). It is important to disentangle whether this pattern is widespread across the northern Antarctic Peninsula. Records of higher spatial and temporal resolution are needed to constrain centennial-scale glacier and ice-mass changes at lower elevations.

Reconstruction of the timing of centennial-scale glacier advances across the region using black moss ages can provide higher spatial and temporal resolution of climate history than other types of archives. By ^{14}C dating mosses, which obtain carbon from the atmosphere directly, a decreased range of error is achievable compared to dating organisms that obtain their carbon from the marine reservoir, i.e., penguins and penguin prey, where old carbon mixes with atmospheric carbon, necessitating a marine reservoir correction to calculate the age. Here, we used calibrated ^{14}C dates from previously ice-entombed black mosses as proxies for glacier advances.

METHODS

We collected black mosses during austral summers in 2019 and 2020 in deglaciated low-elevation terrain on the Antarctic Peninsula and nearby islands. We collected terrestrial black mosses from four sites spanning 62°S to 65°S (Table S1 in the Supplemental Material[1]) using

[1]Supplemental Material. Detailed description of methods for sampling criteria and dating, as well as results for dating and sum probability distributions. Please visit https://doi.org/10.1130/GEOL.S.21824796 to access the supplemental material and contact editing@geosociety.org with any questions.

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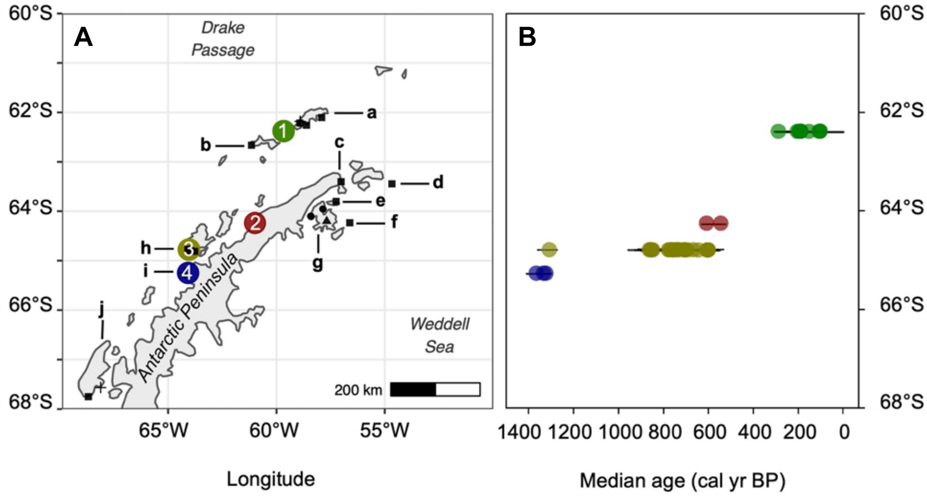

Figure 1. Location and kill dates of black mosses in the northern Antarctic Peninsula. (A) Site locations. 1—Robert Island; 2—Charles Point; 3—Anvers Island; 4—Cape Rasmussen. Other proxies (square—penguin date; triangle—ice core; crosshair—moss; circle—^{10}Be age) and sites mentioned include: a—King George Island, Penguin Island, and Ardley Island; b—Livingston Island; c—Hope Bay; d—Danger Island; e—Devil Island; f—Seymour Island; g—James Ross Island; h—Anvers Island; i—Galindez Island; j—Adelaide Island and Ginger Island. (B) Median calibrated age (cal yr B.P., indicates calibrated ^{14}C years before A.D. 1950) with 2σ ranges (black bars) plotted by latitude.

new strict criteria (see the Supplemental Material). We present the first kill dates from Robert Island, Gamage Point (Anvers Island), Charles Point, and Cape Rasmussen (Fig. 1A). On Anvers Island, samples were collected between Palmer Station and the Marr Ice Piedmont at Gamage Point, and on nearby Bonaparte Point. The kill date represents a minimum age of glacier advance for a location and is specifically an advance age and not a retreat age.

We inspected and cleaned 39 black moss samples under a stereomicroscope for ^{14}C dating. Details of sample treatment, analysis, and age calibrations are provided in the Supplemental Material. All dates reported here represent calibrated yr B.P. (relative to 1950), and all reported ranges are 2σ. We recalibrated previously published black moss and penguin dates (Tables S1 and S2).

For black mosses collected on Gamage and Bonaparte Points (Anvers Island), we estimated the distance from the sample location to the closest edge of the retreating glacier delineated using WorldView-2 satellite imagery (https://earth.esa.int/eogateway/missions/worldview-2) captured on 12 February 2019 and ArcMap GIS (v. 10.7). We used simple linear regression to estimate glacier advance rates (m/yr) for Gamage and Bonaparte Points individually. For a comparison to retreat rates, glacier lines were derived from a digitized 1963 aerial photo (U.S. Geological Survey, series 4422, image 19) and satellite imagery (2004 Quickbird-2, 2011 WorldView-1, and 2019 WorldView-2) and compared to the 2019 glacier edge for Gamage Point and from the glacier edge in 2004 satellite imagery to the 2019 glacier edge for Bonaparte Point.

BLACK MOSS ^{14}C AGES—EVIDENCE FOR GLACIER ADVANCES

At Robert Island (62.3°S; Fig. 1), in the South Shetland Islands, we collected and dated black mosses ($n = 13$) from bedrock and boulders on nunataks and headlands at Coppermine Peninsula. The nunataks are located on the edge of the ice cap on the Robert Island north glacier at a higher elevation than the glacier edge in the deglaciated landscape adjacent to Carlota Cove. Samples collected in the recently deglaciated area were from exposed bedrock outcrops paralleling the glacier edge at Coppermine Peninsula. Median ages ranged from ca. 310 cal yr B.P. to present for kill dates on Robert Island (Table S1).

Charles Point (64.2°S; Fig. 1) is adjacent to the Mouillard Glacier on the Danco Coast of the Antarctic Peninsula. Black mosses were collected from bedrock cracks on a recently deglaciated, east-facing hillside that abuts actively eroding peatbanks and the edge of Cayley Glacier. Non-modern black moss collections made there ($n = 2$) had median ages of 550 and 610 cal yr B.P.

On Anvers Island (64.7°S; Fig. 1; $n = 21$), median ages ranged from 860 to 600 cal yr B.P. for a wide area (~0.5 km^2) where two glaciers are retreating, the Montiel Glacier and an unnamed glacier, which are part of the larger Marr Ice Piedmont (Fig. 2C). The area of deglaciated terrain sampled on Gamage Point (~0.2 km^2 in 2019) is greater than that at nearby Bonaparte Point (<0.1 km^2 in 2019; Fig. 2C). Mosses were collected from varying microtopographic aspects. Dead moss median ages on both points indicate ~250 yr of glacier advance on the Palmer Peninsula. At Gamage Point, the median ages ranged from 850 to 600 cal yr B.P. At Bonaparte Point, the median ages ranged from 860 to 670 cal yr B.P. A single older date outside this range stands out as the oldest among the samples collected on Anvers Island, with a median kill date of 1310 cal yr B.P. (Table S1), and it was excluded from the estimated net glacier advance rate on Gamage Point. We argue that this older sample is not related to the net glacier advance and persisted under local snow/ice ~500 m away from the 2019 glacier edge on Gamage Point. Similarly, three nearby samples with kill dates >850 cal yr B.P. were collected at lower elevations (like the oldest and most westward sample collected on Anvers Island) relative to samples at >35 m elevation on the drumlins traversing eastward toward the glacier edge (Fig. 2C). Excluded dates came from low-elevation samples and were not included in the regression analysis (Fig. 2A). These samples were included in the sum probability distribution and used to define the three phases of glacier advance (Fig. 3). The glacier advance that entombed the mosses above >35 m elevation could have been pinned on this higher-elevation area. Black mosses at lower elevations are likely relics from an earlier event that extended beyond the 35 m elevation area and may have scoured most of the mosses, except the farthest, lowest-elevation samples.

Cape Rasmussen (65.2°S; Fig. 1; $n = 3$) is on the north side of Waddington Bay and the south side of the Wiggins Glacier on the continent. Here, black mosses collected in exposed, east-facing bedrock crevices facing Wiggins Glacier had median ages ranging from 1370 to 1320 cal yr B.P. (Table S1). These are the oldest kill dates presented here, are almost twice as old as some kill dates (860–600 cal yr B.P.) from nearby Anvers Island, and are similar to the lower-elevation outlier from Gamage Point.

TERRESTRIAL EVIDENCE FOR LATE HOLOCENE GLACIER ADVANCES

Our new kill dates ($n = 39$) together with previously published values ($n = 28$) suggest three possible phases of glacier advance in the northern Antarctic Peninsula in the past 1500 yr. Among these are published kill dates from King George Island (Hall, 2007), Anvers Island (Hall et al., 2010; Yu et al., 2016), Adelaide Island (Guglielmin et al., 2016), and Galindez Island (Yu et al., 2016) (Table S1; Fig. 3A). Evidence for the three glacier advances provides well-constrained age estimates for cooler, and perhaps wetter, conditions than present.

Other evidence from terrestrial proxies for past glacier advances and/or cooler atmospheric conditions supports the moss kill dates. Terrestrial evidence in the northern Antarctic Peninsula for late Holocene glacier advances comes from ^{10}Be ages from James Ross Island and

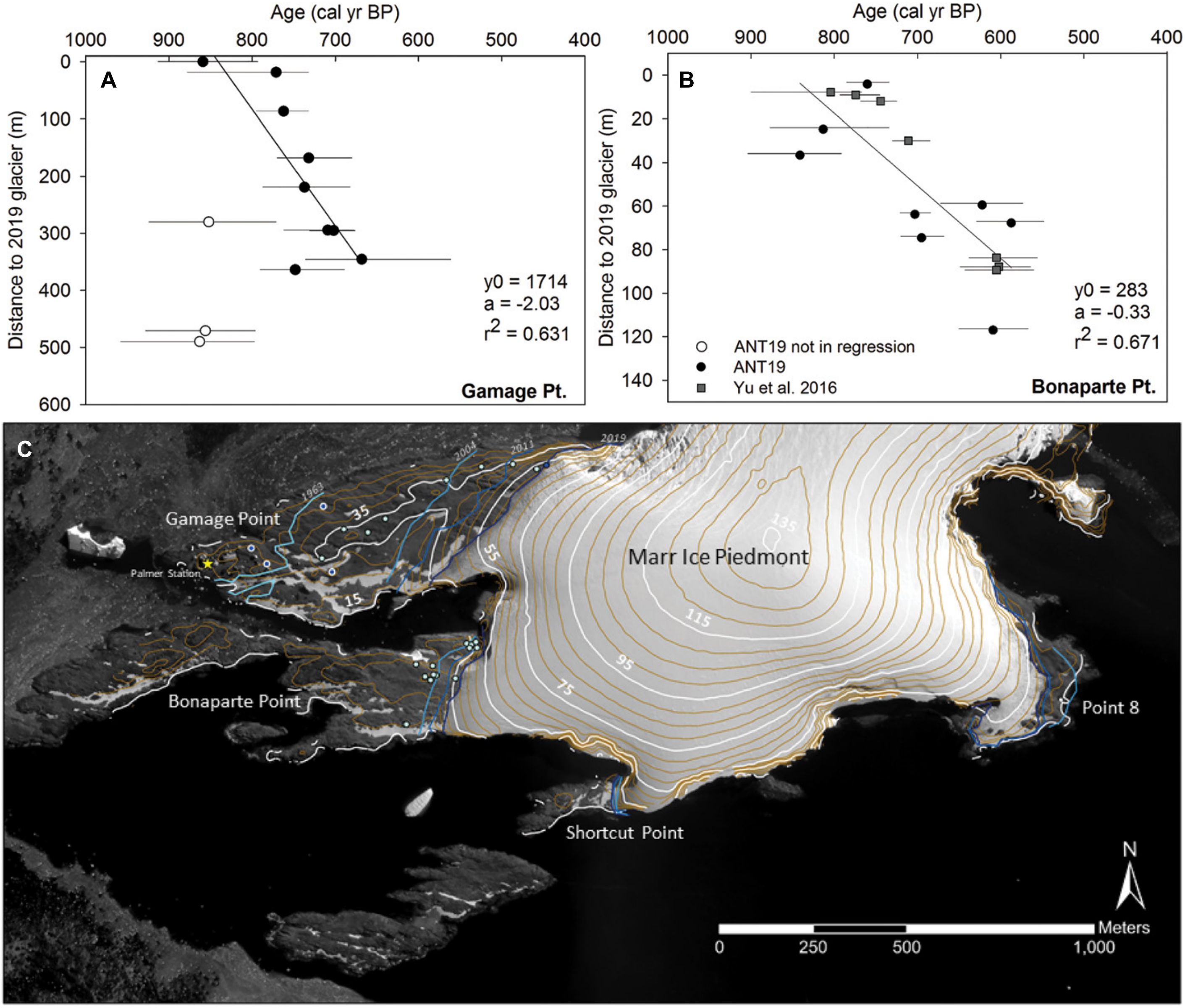

Figure 2. Black moss kill dates and glacier advance rates on south Anvers Island, Antarctica, with median kill dates and 2σ ranges for Gamage Point (A) and Bonaparte Point (B). Distance to the 2019 CE glacier edge allows an estimate for the net advance rate of 2.0 m/yr ($y = 1714 + 2.03x$, $r^2 = 0.63$, $p < 0.001$) and 0.3 m/yr ($y = 283 + 0.33x$, $r^2 = 0.67$, $p < 0.001$), respectively. Open circles were not used in the regression for Gamage Point. (C) Map of collection sites (circles) on Anvers Island near Palmer Station (star). Blue-colored lines indicate former glacier edge extents (1963, 2004, 2011, and 2019 CE) of the Marr Ice Piedmont. Contour lines represent 5 m intervals.

indicates that glaciers were larger at ca. 1300 cal yr B.P. and from 300 to 0 cal yr B.P. (Kaplan et al., 2020), largely coinciding with moss kill dates (Fig. 3; Table S3). Terrestrial evidence from peat records suggests low biological productivity at ca. 700 cal yr B.P. (Charman et al., 2018) and lower bioavailable moisture at ca. 1200 cal yr B.P. and 500 cal yr B.P. approximated from $\delta^{13}C$ cellulose (Royles et al., 2012). Wet intervals over the past 1500 yr identified in peat deposits near Anvers Island (Stelling et al., 2018) coincided with kill dates. Lake sediment records from Signy Island suggest cooler temperatures and extended ice cover based on reduced biological productivity after 1400 cal yr B.P. (Hodgson and Convey, 2005), after 1300 cal yr B.P. (Jones et al., 2000), and at 1350 cal yr B.P. and 500 cal yr B.P. at Livingston Island (Björck et al., 1991).

Marine evidence from Barilari Bay (south of Anvers Island) supports centennial-scale cooler conditions from 2850 to 730 cal yr B.P. and from 730 to 80 cal yr B.P.; the latter coincides with the classic Northern Hemisphere Little Ice Age (Christ et al., 2015). Because Earth's upper-mantle structure in the region is weak (Nield et al., 2014), minor glacier activity is recorded by changes in elevation across paleobeach ridges (Fretwell et al., 2010; Zurbuchen and Simms, 2019). From these beaches, rates of relative sea-level change show evidence for late Holocene glacier advances at 450–250 cal yr B.P. in the South Shetland Islands (Simms et al., 2012). At Joinville Island, erosional beach features and rates of relative sea-level change indicate glacier advance from 1090 to 610 cal yr B.P. and from 440 cal yr B.P. to present, and a phase of warmth and glacier retreat (ice-mass loss) from 1680 to 1090 cal yr B.P. (Zurbuchen and Simms, 2019).

If the climate that promoted glacier advances involved wetter conditions, this may have had an impact on penguin rookery success over time as evidenced by penguin dates (Table S2). It is known that increased snowfall negatively impacts already declining penguin populations (Fraser et al., 2013), and penguins could have responded similarly to wetter conditions in the past. The recalibrated ^{14}C age ranges of

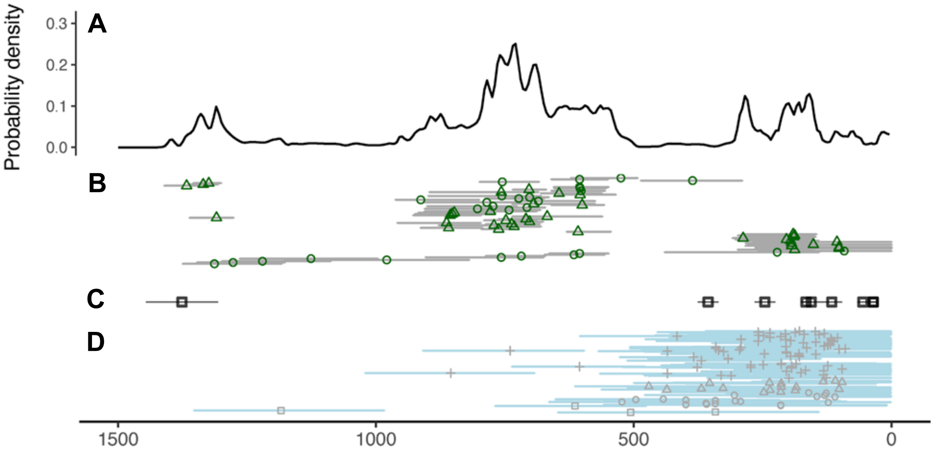

Figure 3. Terrestrial evidence for glacier advances and/or increased snow accumulation on the Antarctic Peninsula. (A) Sum probability distribution of moss kill dates. (B) Moss kill dates with 2σ error bars from this study (triangles) and published (circles) Antarctic Peninsula records (*n* = 67; Table S1 [see footnote 1]). (C) ^{10}Be ages (black squares) with 1σ error bars indicating timing of glacier expansion on James Ross Island (*n* = 9; Table S3). (D) Calibrated median ages with 2σ error bars (blue) of published ^{14}C dated penguin colony remains (gray symbols, *n* = 115; Table S2) from the South Shetland Islands (crosshairs), Palmer Station (circles), and the eastern (triangles) and southern (squares) Antarctic Peninsula.

published penguin remains that are less than 2050 yr old (*n* = 115) overlap (450–0 cal yr B.P.) with the black moss kill dates of ca. 200 cal yr B.P. from Robert Island and King George Island. However, penguin colony ages younger than 1300 radiocarbon years B.P. yielded calibrated ranges that made it impossible to estimate abandonment within the last phase of glacier advance. An abundance of penguin remains from 450 to 0 cal yr B.P. (Fig. 3) also coincides with neoglacial advances during cold phases (Palacios et al., 2020) and diminished penguin activity from 450 to 200 cal yr B.P. from lake records (Liu et al., 2005). Records of moss kill, penguin colony abandonment, glacier advances, and climate cooling appear to be strongly linked.

Glacier Advance Rates

We provide the first estimate, and refine a previous estimate, of past glacier advance rates at Gamage and Bonaparte Points, respectively. At Gamage Point, the linear relationship between moss kill dates and position relative to the glacier edge suggests an advance rate of 2.0 m/yr (Fig. 2A). Median kill dates >850 cal yr B.P. were excluded from the regression. A convergence in ages across Gamage and Bonaparte Points provides a constraint on the cold and/or snowy phase. At Bonaparte Point, the linear relationship indicates an advance rate of 0.3 m/yr (Fig. 2B). This rate (refined by a larger number of dates, *n* = 15) is lower than a previous estimate of 0.6 m/yr (*n* = 7) at the same location (Yu et al., 2016). The pattern of past glacier advance matches the pattern of recent glacier retreat at both Bonaparte Point (~4.0 m/yr; 60 m in 15 yr from 2004 to 2019) and Gamage Point (~8.7 m/yr; 500 m in 56 yr from 1963 to 2019), such that faster oscillations occurred at Gamage Point, and slower oscillations occurred at Bonaparte Point. When comparing the rates of retreat and advance for each point, we found that the rates of recent retreat are much faster than the past advance rates for both Gamage (retreated at 8.7 m/yr and advanced at 3 m/yr) and Bonaparte Points (retreated at 4.0 m/yr and advanced at 0.3 m/yr).

CONCLUSIONS

Our record of moss kill dates reveals and constrains the timing of three phases of glacier advance over the past 1500 yr and provides estimates of glacier advance rates. Although some glaciers advanced simultaneously, local rates varied by almost an order of magnitude on Anvers Island, at 2.0 and 0.3 m/yr. Past glacier advances were far slower than recent retreat rates. Our estimates suggest that a glacier that is receding rapidly today also advanced faster in the past, suggesting dynamic hotspots of glacier activity in the Antarctic Peninsula.

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