From: **Ellen Thomas** em@editorialmanager.com
Subject: Editor Decision - Reject: Invite Resubmission - [EMID:d3f4407d78782835]
Date: May 5, 2015 at 3:20 PM
To: Paul Robert Bierman paul.bierman@uvm.edu

Ref.: Ms. No. G36839
Cold-based, Laurentide ice covered New England's highest summits during the Last Glacial Maximum
Geology

Dear Dr. Bierman ,

I have now received three reviewers' comments on your GEOLOGY manuscript. All three were overall supportive of the work, and so am I, but one reviewer suggested 'reject, invite resubmission' while two asked for 'minor revision'. After reading all reviews and the manuscript, I am convinced that more than minor revision is needed. In fact, what reviewer 3 asks, seems very reasonable to me but could not be accommodated with 'minor revision'. I also agree with reviewer 1 that the data may not uniquely support the conclusions. In addition, I would like to see abstract revised and a short conclusion section inserted in order to more clearly address a broad audience, and make the wider implications of the research more clear to such an audience of non-specialists. I also would like to see a somewhat more informative Figure 1 (e.g., with altitudes shown). When major revisions are thought to be necessary, GOLOGY editors decide to 'reject, invite resubmission'; I strongly encourage
you to carefully consider the reviewers' comments and rewrite your paper for resubmission to GEOLOGY. If you decide to resubmit to GEOLOGY, please outline in your Cover Letter how the new manuscript has been rewritten overall, identify the manuscript as a resubmission of a previous paper and refer to this original manuscript number. You should also include a detailed, point-by-point letter in which you describe your response to all comments by reviewers. Your resubmitted paper will be treated as a new submission and will be subject to further peer review, most probably by some combination of new and repeat reviewers. Acceptance is not guaranteed.

I am appending copies of the reviewers' comments to this message. Thank you for the opportunity to examine this work.

Yours sincerely,

Dr. Ellen Thomas
Yale University
Geology

Reviewers' comments:
Reviewer #1: The manuscript presents measurements of multiple cosmogenic nuclides from three summits in New England. Whether or not the Laurentide Ice Sheet covered the summits during the Last Glacial Maximum has been a topic of great interest for many decades. The authors conclude that the Laurentide Ice Sheet covered the summits during the Last Glacial Maximum, but by frozen-bedded ice, based on high abundances of long-half-life nuclides (10Be and 26Al), and low-abundances of the short-half-life nuclide 14C.

The strength of the manuscript is two fold. It lies in the fact that there are very few published datasets yet to use the powerful in-situ 14C tool, and this study nicely illustrates the advantage of being able to measure multiple nuclides, each with a different half-life, in the same samples. The second strength has to do with being a topic of great interest, at least at the regional scale.

Despite these strengths, there are a couple of fundamental issues with the manuscript in its present form, and there are number of more minor things, per usual, that could be done to help streamline this draft.

Foremost is that the data do not uniquely support the conclusions made by the authors. An alternative interpretation compatible with the data is that the summits were covered by local glaciers/ice caps during the Last Glacial Maximum. Cover by local ice for 29 kyr could also produce the decay needed to re-set the 14C clock. In fact, as it stands, the authors already invoke a period of shielding by local glaciers both before and after the Last Glacial Maximum in order to explain the 14C concentrations. So it is not a stretch, and one may even argue more likely, that it was local ice that covered the summits throughout the Last Glacial Maximum and not Laurentide ice. Furthermore, the lack of burial recorded in the Al/Be system also lends support to the fact that the peaks may have not been buried by ice sheet ice. Although the Al/Be system cannot be used to definitively support lack of burial during the Last Glacial Maximum (or any duration of cumulative burial less than ~100-200 ky, depending on Be and particularly Al error), it does suggest that it is unlikely that the peaks were covered during Quaternary average glacial maxima.

In any case, unless the authors treat this scenario explicitly, the paper is not acceptable for publication in its current form. It is possible that after some re-working, they can make a convincing case for one interpretation over the other, in which case it may be suitable for Geology. Maybe ice sheet surface profiles, extended northward from the Last Glacial Maximum terminus position, could bolster the CRN data?

A second issue is the presentation of the research, and is related to the above. I find it ambiguous whether the authors are meaning to justify the research by testing a model of ice sheet occupation of the summits that is supported by the literature (lightly weathered erratics, till patches with weak soils) with cosmogenic isotope measurements. Or whether they a priori assume based on this (qualitative) evidence that the summits were occupied by the ice sheet during the Last Glacial Maximum, and are rather doing the research to constrain the pattern of erosion and sub-ice conditions.

For example, on line 47, near the beginning of the paper, regarding the qualitative data presented in past literature, the authors write "Testing these observations has been stymied by the difficult of dating…" The words imply that the point of this study is to test the observation with improved approaches.

Versus line 132 in the discussion, where the authors write "When considered along with the geologic evidence that the summits were overrun by ice…" and then continue to make that assumption throughout duration of the paper.

My feeling is that these authors can do better with this manuscript with more time spent on it, and perhaps they can re-tool it so it includes the obvious possibility of local ice cover that the manuscript ignores in its present form. I could see after a re-write that this paper might be suitable for Geology, it has a lot of potential.

Minor issues, hoping that authors can use these comments to improve/streamline manuscript:

Line 24, replace "considering" with "assuming" ?

Line 35, ice or snow persisted on the peaks for millennia after (AND PRIOR to) the last glaciation of the summits.

Line 75, sentence beginning with "Comparison.." This sentence is virtually the same as the previous one, condense.

Line 78, "…several hundred ky…" is a bit long, but in any case, this depends on the uncertainty of Be and Al measurements, which are quite low these days, especially Al data at PRIME.

Line 82. It mentions that "glacially polished" bedrock was sampled, but nowhere else in the paper is it mentioned what ages came from these types of samples, nor are sites in the Tables described as glacially polished.

Line 96. Data section. Would be helpful to see errors in text.

Line 98. Make consistent reporting of significant digits. Also 9.28 is younger than what text says is youngest age on line 101 as 9.6 ka.

Line 102. Says 153 ka is oldest age, two sentences prior says 156 ka.

Line 109. Sentence beginning with "At 2 SD…" should be condensed with the beginning of the paragraph when the text explains the concordance of Al and Be ages, otherwise repetitive.

Line 157. You write that it takes 29 ky of burial to zero a 14C inventory. At some point (even in sup) you should explain where this value comes from, is it from a paper (then cite), or based on a certain measurement ability to distinguish from background?

Line 159. The "…plus 29 ky…" should be ">29 ky"

Line 181. "around" vs. using the "~" symbol. Be consistent.

Figure 3 caption. Cite benthic d18O data.

Figure 2. I would find it helpful to see all the data (ages) on this figure.

Figure 3. The vertical shaded zone labeled "minimum burial (29 ky) to remove pre-LGM 14C" is only ~20 ky wide.

Reviewer #2: I have given this paper the highest rating possible and have only indicated minor revisions to take care of some minor editorial changes, mostly with references.
This is an excellent paper and one that gives us a major leap forward in our understanding of the overall geomorphic alteration of landscapes by ice sheets. Although often suspected, this paper finally proves that there was minimal erosion across the tops of high mountain peaks in northern New England. It takes advantage of both Be and Al cosmogenic ages but also employs the use of new insitu measurements of C14. It is clear from this paper that the overall relief of New England is increasing with repeated glaciations as high peaks are essentially not eroded due to a frozen bed and many valley areas are heavily scoured with rock surfaces below sea level, for example the Connecticut Valley. I was especially astounded at the high inheritance of blocks in deposits of periglacial origin. The paper sets up many spin off studies, by establishing the technique, and also sparking many ideas about where to try this next. For example are peaks at slightly lower elevations, such as Mt. Monadnock and the quartzite ridges of western New Hampshire heavily scoured or not? The paper also sheds some light on the amount of snow cover that occurred during the last glacial period both before and after the arrival of continental ice. This has importance to deciding whether cirque glaciation is possible as the continental ice sheet arrived or immediately following its recession from the high peaks.
The main contribution is that it shows how to use the cosmogenic technique as a tool for assessing erosion in a glaciated terrain with varying bed conditions.

Here are some minor editorial changes that should be made by line number:

Line 136 - Should Briner et al. be 2014 or is Briner et al. 2006 missing from reference list.

Line 161 - I have read this line many times - Should this say "colder" than today instead of "warmer".

Line 271 - Goldthwait, 1970 reference should come after the Goldthwait 1940 reference.

In supplement references:

Shouldn't the title of the "References Cited" be "Additional References Cited" since many of the references in the main paper are not listed here.

The two Anderson references are not used or else I could not find them.

"COST-727" should be "COST, 2007"

The Dorian reference can be omitted since it is cited in the main paper text.

Reimer et al, 2014 on Table S4 is not referenced here.

Reviewer #3: This is an exciting report that is low on sample number, rich in data and long on interpretations that are forced by the multiisotope data. I would like the authors to (1) better explain the local spatial/topographic context of where they collected samples, since that context seems central for their inferences about snow/ice cover and its persistence; and (2) reassure me and other readers that the 14C production rates are correct.
This work offers a novel mechanism for producing or maintaining relief in an environment shaped by ice erosion. Things that concern me.
1. Sample locations/local topographic relations. You necessarily are working with a small number of samples and much of your interpretation rests on being able to interpret where these blocks came from, their local topographic context, and their recent history. Samples clearly are local and some reflect a long history of exposure. But could the others be "lower" blocks from the same outcrop or covered with some till until recently? The answers and interpretations are important, but of particular significance for the 14C concentrations and for the other samples that are "too young".
Are the sample sites places that seem likely to have accumulated snow or rime both before and after the LGM? Your illustrations suggest these are narrow, windblown summits that do not accumulate much snow or long-lasting rime in the modern environment. Adjacent to such areas are places where drifts are persistent in the modern. I presume if you had photos of the outcrop areas that we'd see them in the ms?
2. Three-isotope system and 14C. Having a three-isotope system is remarkable and 10Be and 26Al are a good and well-understood check. Is 14C as well understood? How well is the production rate known? Is 14C geochemically stable after it forms under all conditions? A lower production rate or having just a little more 14C would solve several issues. And is analytical uncertainty such that you really need to bury the 14C samples for 5 half-lives, or would 3 or 4 half-lives do?
3. Didn't summit areas emerge even earlier? As the ice front was retreating, the regional ice surface was lowering such that these high-elevation sites would have poked out first; the nearby and more distant low-elevation dates provide only a lower limit for deglaciation of sites 1 km above them. Is it a close limit? What happened to Laurentide ice during the time between the stable Cape Cod margin and Pineo Ridge time? Was the ice profile essentially the same until BA time? I know we don't have a clear sense of the regional ice profile or how the basal shear stress changed over time, but the ridge sites should have been covered last and first out.
4. Paleoclimate? Is the modern temperature and a plausible lapse rate consistent with cold-based ice at 21 ka….and cold-based both on Mt. Washington and on Little Haystack, some 300 m lower. Could the summit areas have been in the clouds even more than at the present, which is true for some ranges.

Comments/suggestions keyed to line numbers in the manuscript
29-32. Invert ideas a bit or break into two sentences; your Geology readers aren't familiar with cosmogenic 14C and you start with the inference (snow or ice covered)….rather than the young accumulation ages
34-35. Hope you can develop this idea in a plausible manner. None of these summits hold snow well in the modern environment—they're just too windy.
39. Throw in Little Haystack and its elevation here? Snow and rime covered, perhaps, but generally the cover is thin.
59-61. Wouldn't you guess that these summit areas would have been exposed somewhat earlier than the valley sites as ice thinned rapidly and mainly flowed through nearby low areas?
67. This story of retreat seems half-told. What happened over the next 10,000 years between Cape Cod and the readvance north of the Presidential Range? Does the ice profile relax and thin early in this process, exposing the summit areas, or only after ~15 ka? I know you are out of room, but you could fill a bit of this gap…since there is quite a bit of detail in this section!
68. Why accurate?
70. Particularly true in high-relief terrain where different portions of the same ice mass are behaving differently?
71. "that may" (for involving)
74. Though it is difficult to get a unique solution.
82. "Frost-riven"? Possible to tell where they came from, or only that they were "local"? In one sense it doesn't matter, since you have "too much " exposure. In another sense, you may have gotten different apparent exposure ages from blocks that represent lower parts of depth profiles in bedrock or beneath and eroding till cover. The young ages are a challenge.
88. Say from where? (one Mt. Washington; one from Katahdin)
90. Is the 14C content of samples stable—any mineralogic or microfracture effects?
100. 10Be ages have smaller errors, right?
102. Is there meaning in this "too young" value?
114. The CRN evidence shows that erosion was ineffective locally; is there any morphologic evidence that allows you to generalize these results or to know how far down the mountain ranges you'd need to go to find effective erosion? Little or no erosion from Mt. Washington along the range to Haystack? Little erosion, but only in limited areas around summits?
130. Young or too young ages—interpretation possible? See line 167 as well.
138. On several of ….
150-151. Do the 14C data allow a shorter time? Could these samples have been below a thin till cover without changing the 10Be exposure age significantly (since it is complex in any case)? The interpretation based on 14C seems too long for Laurentide ice cover, cirque glaciers would not have covered these sites and it is hard for me to believe that sites near these sharp summits could have preserved snow cover long term unless the wind regime was completely different than it is at present or you were in a drift zone.
168-169. Could you do all of this with a thin till or rock-block cover? Would the heavily dosed samples have been reset significantly?
170-174. So it is easy to imagine persistent cold during 800 years of the Younger Dryas, but most evidence seems to suggest no cirque

glaciers during that time period. Before and after YD it was warm, at least according to the pollen in local bogs and many other things we believe.   Summer should have been warm, melting rime ice and any snow cover away from persistent drifts.   So it seems as though you need to invoke a different lapse rate, a persistent cloud cap, or some other mechanism that makes these mountain areas behave like the High Arctic?

179.   This idea would seem more plausible to me if it seemed as though sample sites were likely locations of long-lived drifts at present, and thus permanent drifts during colder times. Absent drifts, why not invoke a thin cover of drift that eroded away?   The rocks are too hard for the removal of significant thicknesses in a short period.

183-188. Cirque glaciers before Laurentide ice arrives seem reasonable, but what mechanism would allow them to extend up to cover the windswept summit areas at Washington and Katahdin…..and Little Haystack? Climate would not only have to be colder, but very different. Could the 14C ages be too young for some other reason?

190-192.   A little challenging to have it both ways?

200.   But large elevation difference between Mt. Washington and Little Haystack—at PMP at all elevations in between?

331.   Why do B and D include ages?   Note in caption?

332.   Same as PTDK-7, analyzed for 14C?

DP Dethier

Geology

Cold-based, Laurentide ice covered New England's highest summits during the Last Glacial Maximum

--Manuscript Draft--

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Cold-based, Laurentide ice covered New England's highest summits during the Last Glacial Maximum

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Abstract

The basal thermal regime of vanished ice sheets is not well constrained. The abundance of ^{10}Be and ^{26}Al in samples collected near the summits of Katahdin and Mt. Washington is 2 to 8 times higher than expected for a single period of exposure, considering that continental ice covered all of the highest New England peaks during the Last Glacial Maximum and did not leave northern New England until 14-16 ka. Bedrock and frost-riven blocks from the top of Mt. Washington have exposure ages up to 153 ka, bedrock from the top of Little Haystack on Franconia Ridge has an exposure age of 60 ka, and a block sample from the summit of Katahdin has an exposure age of 36 ka. In contrast, *in situ* ^{14}C exposure ages from the mountain tops are young (ca. 11-13 ka) suggesting that high elevation sampling sites were snow- or ice-covered for at least five ^{14}C half-lives ($t_{½}$=5.7 ky: ≥29 ka) and until the end of the Pleistocene, allowing ^{14}C produced during interglacial exposure to decay. The isotopic data are consistent with the summits of New England being covered in part by cold-based, continental ice unable to erode a significant thickness of rock. The *in situ* ^{14}C ages suggest thin, local ice carapaces or perennial snow fields persisted on the peaks for millennia after regional deglaciation.

Background

Katahdin (1606 m) and Mt. Washington (1917 m) are the highest peaks in Maine and New Hampshire (Figure 1). Their rocky summits are barren, windblown, and can be snow-covered for five to six months of the year (Havens, 1960). Shattered bedrock block fields testify to periglacial activity (Davis, 1989; Goldthwait, 1940).

The glacial geology of these peaks has been studied for over 150 years (Thompson et al., 1999). Hitchcock (1878) described evidence for ice overriding Mt. Washington’s summit. Tarr (1900) and Goldthwait (1916) found small erratics on the summits of Katahdin and Mt.

Washington. Later, Goldthwait (1940, 1970) noted that erratics on the uplands of the Presidential Range were only slightly weathered and concluded that the last overriding ice dated to the Last Glacial Maximum (LGM). Davis (1976, 1989) used similar evidence to reach the same conclusion for Katahdin. Testing these observations has been stymied by the difficulty of dating glacial retreat because organic material, such as wood and charcoal, is scarce in glacial and immediately post-glacial deposits. Thus, deglacial chronologies in New England have been primarily based on minimum-limiting radiocarbon ages from pond and bog bottom sediments, for which the lag time between deglaciation and the accumulation of organic material is uncertain, especially in alpine terrain where vegetation is scarce and the onset of primary productivity in lakes is delayed (Davis and Davis, 1980; Bierman et al., 1997).

New geochronologic approaches allow refinement of glacial chronologies. Varve counting, now supplemented with paleomagnetic data and radiocarbon ages of terrestrial macrofossils within varves from glacial Lake Hitchcock, provides robust age control for deglaciation of the Connecticut River valley (Ridge et al., 2012) and central New England; regional deglaciation of the Mt. Washington and Little Haystack sample sites had occurred by about 14 ka. The measurement of nuclides produced in rock by cosmic-ray bombardment (Lal, 1988; Balco, 2011) provides direct dating of rock surfaces exposed by deglaciation. For example, the area around Katahdin was deglaciated between 15 and 16 ka (Davis et al., accepted) and that the area around Mt Washington was clear of continental ice before 13.8 ka (Bromley et al., 2015). Application of cosmogenic nuclides elsewhere in New England (with data recalculated using the regional production rate, Balco et al., 2009) shows that Laurentide ice remained at its maximum extent on Martha's Vineyard until ~27 ka and then, over the next few thousand years retreated several tens of km to Cape Cod (Balco et al., 2002) and coastal Connecticut (Balco and Schaeffer, 2006).

Accurate cosmogenic surface exposure ages are predicated on the assumption that enough rock was eroded by glaciers to remove nuclides produced during prior periods of exposure (Bierman et al., 1999). Landscapes covered by cold-based, non-erosive glacial ice violate that assumption, and preserve a complex isotopic record involving multiple periods of exposure and burial (Bierman et al., 1999; Harbor et al., 2006; Corbett et al., 2013; Briner et al., 2014). In such cases, cosmogenic nuclides with different half-lives (e.g., ^{10}Be, 1.4 My; ^{26}Al, 0.7 My; ^{14}C, 5.7 ky) can be used together to constrain complex exposure scenarios (Granger and Muzikar, 2001; Briner et al., 2014). Comparison of nuclides with shorter vs. longer half-lives provides insight about exposure and burial durations (Corbett et al., 2013). In glacial landscapes dominated by cold-based ice, the ratio of ^{10}Be and ^{26}Al can be used to detect exposure followed by burial only if that burial lasts several hundred ky; however, the short half life of *in situ* ^{14}C makes it useful for detecting burial of at least a few thousand years (Miller et al., 2006; Briner et al., 2014; Goehring et al., 2011).

Methods

We collected samples from frost-riven bedrock blocks and glacially polished bedrock surfaces (Figure 2; Supplementary Information, Table S1) on and near the summits of Katahdin in Maine (n=2), Little Haystack (n=1) in New Hampshire, and on and near Mt. Washington's summit in New Hampshire (n=6). For each sample, between 25 and 41 g of quartz was dissolved and Be and Al were extracted at the University of Vermont (Kohl and Nishiizumi, 1992; Bierman and Caffee, 2002; Table S2). We made isotopic analyses at Lawrence Livermore National Laboratory. About 5 g of pure quartz from two of the samples was processed for *in situ*

^{14}C analysis following Lifton et al. (2001) and Miller et al. (2006) using extraction and purification systems at the University of Arizona (Table S3). The ^{14}C content of the samples was analyzed at the Arizona AMS Laboratory and blank-corrected following Lifton et al. (2001), using data reduction techniques described by Hippe and Lifton (2014). Exposure ages (^{10}Be and ^{26}Al) were calculated using the CRONUS calculator (wrapper script: 2.2, main calculator: 2.1, constants: 2.2.1, muons: 1.1, Balco et al., 2008) and Lal (1991)/Stone (2000) time invariant scaling (Balco et al., 2008).

Data

Samples from on and near the summits of Katahdin, Little Haystack, and Mt. Washington (1326 to 1896 m asl) have single nuclide ^{10}Be, ^{26}Al, ^{14}C, and exposure ages ranging from 9.28 to 156 ka (Table S1; Figure 3). Because ^{10}Be and ^{26}Al exposure ages are positively and linearly correlated (R^2=0.996; slope=1.03), we use the uncertainty-weighted average of ^{10}Be and ^{26}Al ages for discussion and in figures. The youngest average exposure age (9.6 ka, PTK-06) is from a bedrock sample on the summit of Katahdin. The oldest average exposure age (153 ka, PTMW-03) is from a frost-riven block on the summit of Mt. Washington. In general, average exposure ages from Mt. Washington are older than those from Little Haystack and Katahdin. However, *in situ* ^{14}C exposure ages on samples from the summits of Katahdin (PTK-07) and Mt. Washington (PTMW-03) are much younger (11.0 and 12.7 ka) than corresponding mean ^{10}Be and ^{26}Al ages (35.6 and 153 ka, respectively). Samples collected near one another have very different ages. For example, four samples from blocks at Goofer Point on Mt. Washington have average exposure ages of 17.9, 18.4, 26.8, and 71.3 ka. At 2 SD, $^{26}Al/^{10}Be$ ratios for all samples from the uplands of Katahdin and Mt. Washington are indistinguishable from the $^{26}Al/^{10}Be$ production ratio of

6.75 assumed by the CRONUS calculator (Balco et al., 2008) as is the average ratio of all samples in this study (6.68±0.39, 1 SD, n= 9).

Discussion

The Laurentide Ice Sheet did not effectively erode most of the upland rock surfaces we sampled. ^{10}Be and ^{26}Al ages for seven of nine samples collected from the summits and uplands of Katahdin, Little Haystack, and on or near Mt Washington are greater, in some cases much greater, than the ~14-16 ka regional deglaciation age (Bromley et al., 2015; Davis et al., accepted; Ridge et al., 2012) around the peaks (Figure 3). One sample from the summit of Mt. Washington, PTMW-03, has an average ^{10}Be and ^{26}Al exposure age of 153 ka, more than 10X the age of regional deglaciation of ~14 ka (Ridge et al., 2012). Similarly, a sample from the summit of Katahdin has an average ^{10}Be and ^{26}Al exposure age of 36 ka, more than 2X the regional, Laurentide deglaciation age of 15-16 ka (Davis et al, accepted).

Spatial variation in the effectiveness of glacial erosion in the New England uplands is likely due to heterogeneous plucking and abrasion of rock resulting from basal thermal regimes very near the pressure melting point (e.g., Briner et al., 2014). Some samples carry the equivalent of tens of thousands of years of surface exposure. Other samples carry inherited ^{10}Be and ^{26}Al equivalent to only a few thousand years of pre-LGM surface exposure. Only two of nine samples (a rock glacier block well below the summit of Mt. Washington, PTMW-04, and a bedrock sample on the summit of Katahdin, PTK-06) have average exposure ages (12.6 and 9.6 ka, respectively) consistent with (but younger than) the accepted timing of northern New England Laurentide ice sheet deglaciation (14-16 ka).

When considered along with the geologic evidence that the summits were overrun by ice in the late Pleistocene (isolated pockets of till with poorly developed and thus young soils), our data indicate that most samples contain ^{10}Be and ^{26}Al produced during at least the previous interglacial, when the New England landscape was ice-free. Such isotopic inheritance has been interpreted elsewhere (e.g., Bierman et al., 1999; Briner et al., 2006; Corbett et al., 2013; Miller et al., 2006; Briner et al., 2014) as evidence for the presence of cold-based ice, frozen to the bed. Because rock surfaces on New England's highest peaks contain concentrations of cosmogenic nuclides that yield ages greater than the timing of regional deglaciation, these surfaces were not substantially eroded during the LGM.

Measuring multiple nuclides in single samples clearly indicates that most of the nuclides we measured were produced during an earlier period of exposure followed by a period of burial and preservation under ice rather than by continuous exposure of the summits as nunataks. For example, two summit samples (MW-03 and PTK-07) have high average ^{10}Be and ^{26}Al exposure ages (153 and 35.6 ka) but *in situ* ^{14}C ages of only 12.7 ka and 11.0 ka, respectively. Together, the multiple isotope data demonstrate two different periods of exposure separated by a period of burial during which ^{14}C produced during the earlier period of exposure decayed away but long-lived ^{10}Be and ^{26}Al remained; otherwise, ^{14}C would be present at saturated (secular equilibrium between production and decay) concentrations and ^{14}C ages would exceed the regional deglacial age of 14-16 ka. Because the ^{14}C ages are less than the regional deglacial age, we presume that burial related to the LGM lasted at least five ^{14}C ages half-lives (≥29 ky, Figure 3) allowing all pre-LGM ^{14}C in these samples to decay away.

We can use multiple nuclide data to constrain better the timing of summit burial and exposure. The ^{26}Al/^{10}Be ratio in New England summit samples (average 6.68±0.39; Table S1) is indistinguishable from the nominal production ratio of these two nuclides (6.75; Balco et al., 2008) precluding long burial times (100s of ky) after initial exposure. The ^{14}C data mandate at least 29 ky of burial before re-exposure of the summits ~12 ka. Using this metric, data from all samples except PTMW-03, PTK-06, and PTMW-04 are consistent either with initial exposure beginning between ca. 102 ka and 47 ka (stated ages on Figure 3 and in Table S1 plus 29 ky of burial around the LGM when no nuclides were produced) when climate was substantially warmer than today (Figure 3), or with different but shallow depths of erosion during the LGM. However, PTMW-03, with an effective average exposure age of 153 ky requires additional exposure prior to MIS 6, the previous glacial period. Using the LGM and ≥ 29 ky of burial inferred above as an analogy, initial exposure of this sample must have occurred ≥ 200 ky (Figure 3). Samples PTK-06 and PTMW-04 have ^{10}Be and ^{26}Al mean ages less than regional deglaciation and so must have been eroded deeply enough that all inherited nuclides were removed.

The similarity of the ^{10}Be and ^{26}Al average age for a Katahdin sample (PTK-06; 9.6 ka), the rock glacier block (PTMW-04; 12.6 ka), and the *in situ* ^{14}C ages (12.7 and 11.0 ka) suggests that cold conditions and thus ice/snow cover persisted in the uplands until the early Holocene. The cosmogenic isotopic data are consistent with permanent snowfields or non-erosive ice carapaces many meters thick covering the summits of Katahdin and Mt. Washington after deglaciation, a common phenomena in the Arctic during the Little Ice Age (Anderson et al., 2008). It seems less likely but plausible that seasonal snow and rime ice cover since ~15 ka could be responsible for the young ages (see Supplemental information). Lower-than-expected exposure ages could also result from rock surface or till erosion (Gosse and Phillips, 2001) or the frost-heaving of blocks (Hallet and Putkonen, 1994). However, the paucity of till and the hardness of sampled rock, as well as the high ^{10}Be and ^{26}Al ages of other summit samples, suggest snow or ice cover is the most likely reason for young ages.

The need for ≥ 29 ky of burial to decay away pre-LGM ^{14}C mandates that ice carapaces also covered the summits starting at least around 40 ka because sea level records indicate that major expansion of the Laurentide Ice Sheet did not begin until ~ 31 ka (Lambeck et al., 2014) and the Laurentide was not fully expanded until ~ 27 ka (Balco et al., 2002). These accumulations of ice on the summits may have fed pre-LGM cirque glaciers that cut the cirques on both Katahdin and Mt. Washington (Waitt and Davis, 1988) before being overwhelmed by continental ice which likely advanced through Maine ~ 29 ka based on calibrated radiocarbon ages of shells, paleosols, and wood found in the basal sections of lake cores (Dorion, 1997; Table S4). The cold-based ice we identify using cosmogenic nuclide measurements likely helped preserve the cirques from erosion by continental ice. Post-LGM, climate warmed and equilibrium lines rose too quickly for the cirques to be reoccupied by alpine ice after regional deglaciation (Loso et al., 1998; Waitt and Davis, 1988) although the discrepancy between summit ^{14}C exposure ages and regional deglaciation is consistent with ice on the summits persisting after deglaciation.

Data from three different cosmogenic nuclides produced *in situ* in New England summit outcrops show that ineffective glacial erosion, and thus the presence of cold-based ice, frozen to the bed, is not limited to polar regions (e.g., Bierman et al., 1999; Briner et al., 2014), high latitudes (Marquette et al., 2004), or the thin ice sheets of the mid-continent (Colgan et al., 2002). Comparison with samples collected at lower elevations (Davis et al., accepted; Bromley et al., 2015) shows that weakly erosive ice was restricted to the summits, likely because ice was thinner and below the pressure melting point only there. The limited distribution of cold-based ice we infer fits well with the small number of New England boulders carrying significant concentrations of inherited nuclides (Balco et al., 2002, 2009; Balco and Schaefer, 2006; Davis et al., accepted; Bromley et al., 2015) and suggests that most Laurentide boulders came from areas where the ice was warm-based and erosive. Global ice volume (Lambeck et al., 2014) was at its greatest for <10 ky, limiting the time New England summits were covered by continental ice. *In situ* ^{14}C data show that ice covered the highest summits of New England until early Holocene warming exposed the outcrops we sampled.

Acknowledgments

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Figure Captions

Figure 1. Location of sampling sites in New Hampshire and Maine at Katahdin, Little Haystack, and Mt. Washington indicated by triangles.

Figure 2. Location of samples and photographs of two sample sites. A. Overview of Katahdin showing location of summit samples. B. Sample site PTK-07 on the summit of Katahdin. C. Overview of Mt. Washington showing location of summit samples (PTMW-01,-02,-03, and PTD94-20, 21) and rock glacier block sample (PTMW-04). D. Sample site on Little Haystack, PTD94-19.

Figure 3. Schematic history of exposure of samples included in this paper. Benthic ^{18}O record is proxy for global ice volume. Grey bars indicate uncertainty-weighted average (^{10}Be, ^{26}Al) exposure age for each sample. White arrows represent *in situ* ^{14}C exposure ages. Grey shaded

area represents five half-lives of ^{14}C (~29 ky) required to decay ^{14}C created prior to overrunning by Laurentide Ice Sheet. Regional deglacial age (14-16 ka) shown by dotted line. Two isotope diagram (inset) shows that $^{26}Al/^{10}Be$ ratios samples are concordant with no substantial burial after initial exposure. Error bars are 1 SD.

Figure 1. Bierman et al.

Figure 2. Bierman et al.

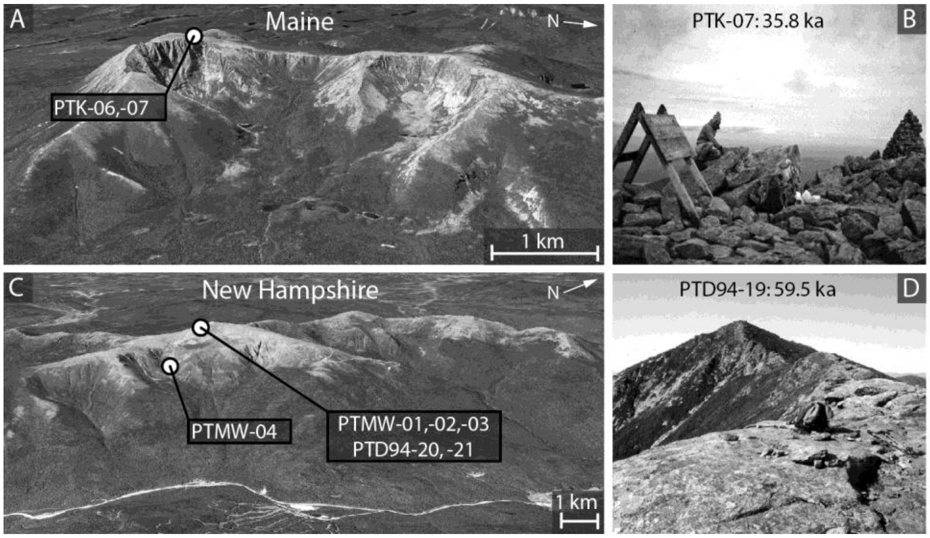
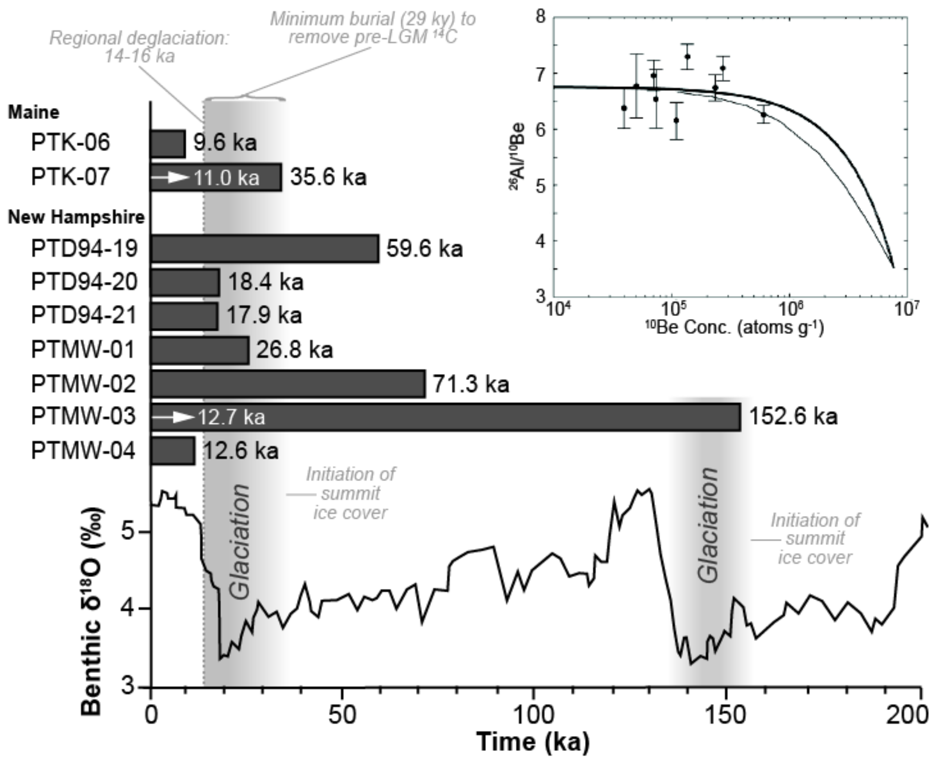


Figure 3. Bierman et al.



Supplemental Information – Bierman et al.

1. Laboratory and data reduction methods

For ^{10}Be and ^{26}Al analysis, about 250 ug of 1000 ppm SPEX ^{9}Be carrier was added to each sample and to the dual process blanks included with each batch of 6 samples. If needed, ^{27}Al carrier was added to samples and about 2000 µg of ^{27}Al (1000 ppm SPEX Al standard) was added to the process blanks. We removed two small aliquots (representing 2.5% and 5% of the sample, respectively) from each sample directly following digestion. Using these aliquots, the total mass of Al and Be was quantified using Inductively Coupled Plasma Optical Emission Spectrometry. Samples were oxidized, mixed with Ag powder, and packed into cathodes for isotopic analyses at Lawrence Livermore National Laboratory.

Al data were normalized to standard KNSTD9919 with an assumed $^{26}Al/^{27}Al$ ratio of 9919 $x10^{-15}$. Be data were normalized to standards LLNL1000 and LLNL3000 with assumed $^{10}Be/^{9}Be$ ratios of 1000 and 3000 x 10^{-15}. Median ratios (and one standard deviation) for blanks processed with samples from New England were $2.40 \pm 1.81 \times 10^{-15}$ for $^{26}Al/^{27}Al$ (n=8) and $2.44 \pm 0.23 \times 10^{-14}$ for $^{10}Be/^{9}Be$ (n=9). These ratios were subtracted from measured ratios and the uncertainty propagated in quadrature.

Approximately 5 g of pure quartz from two of the samples (PTDK-7 and PTMW-3) was processed for *in situ* ^{14}C analysis following Lifton et al. (2001) and Miller et al. (2006) using extraction and purification systems at the University of Arizona. *In situ* ^{14}C was extracted from each sample using the recirculating system and techniques described by Lifton et al. (2001), Pigati et al. (2010), Miller et al. (2006). The ^{14}C content of the samples was analyzed at the Arizona AMS Laboratory and blank-corrected following Lifton et al. (2001), using data reduction techniques described by Hippe and Lifton (2014).

Exposure ages (^{10}Be and ^{26}Al) were calculated using the CRONUS calculator (wrapper script: 2.2, main calculator: 2.1, constants: 2.2.1, muons: 1.1, Balco et al., 2008) assuming the northeastern North American production rate and Lal (1991)/Stone (2000) time invariant scaling (Balco et al., 2008). Ages for *in situ* ^{14}C were calculated using a version of the CRONUS calculator modified for use with *in situ* ^{14}C, and Lal (1991)/Stone (2000) time invariant scaling. Global production rates for *in situ* ^{14}C were derived using calibration datasets from Lake Bonneville, Utah (Lifton et al., in press), northwestern Scotland (Dugan, 2008), New Zealand (Schimmelpfennig et al., 2012), and western Greenland (Young et al., 2014). Each dataset was first recalculated following Hippe and Lifton (2014). Replicate analyses on individual samples were combined using inverse relative error-weighted means, and each site was then calibrated to a sea level, high latitude (SLHL) production rate separately using CRONUS calculator code. The arithmetic mean and standard deviation of the site-derived SLHL production rates was then computed and used in the exposure age calculations.

2. Snow and ice cover calculations

It is possible that seasonal snow or ice cover could have reduced exposure ages For example, to reduce an exposure age from 14.5 to 12 ky, requires a nearly 20% reduction in cosmic ray dosing, which could be achieved by covering the samples with ~35 cm of water equivalent year round (Schildgen et al., 2005). Since soft rime and wet snow, both common on the summits, have densities ranging between 0.2 and 0.6 g cm^{-3}

(COST, 2007), to achieve the reduction in age we measure there would need to be between 1 and 3 m of frozen material present for 6 months per year since deglaciation 15 ky. This seems to be more ice and snow than is present today.

Table S1. Sample location and age data, New England Summits

Sample	Site	Elevation (m)	Latitude	Longitude	Type	Thickness (cm)	^{26}Al Age (yr)*	^{10}Be Age (yr)*	Uncertainty-weighted average exposure age (yr)	^{26}Al/^{10}Be Ratio$^{@}$	^{14}C Age (yr)$^{\#}$
PTD94-19	Franconia Ridge: Little Haystack	1575	44.13620	-71.64402	Bedrock	3.0	59860 ± 3210	59390 ± 3310	59630 ± 2300	6.74 ± 0.23	
PTD94-20	Mount Washington: Goofer Point	1896	44.26982	-71.30483	Block	3.0	18010 ± 1600	18570 ± 1010	18410 ± 850	6.54 ± 0.51	
PTD94-21	Mount Washington: Goofer Point	1896	44.27004	-71.30483	Block	3.0	18200 ± 1030	17650 ± 950	17900 ± 700	6.96 ± 0.26	
PTMW-01	Mt Washington: Goofer Point	1896	44.27049	-71.30483	Block	1.0	25370 ± 1730	27790 ± 1500	26750 ± 1130	6.15 ± 0.33	
PTMW-02	Mt Washington: Goofer Point	1896	44.27049	-71.30483	Block	3.0	73910 ± 4140	69350 ± 3650	71340 ± 2740	7.09 ± 0.22	
PTMW-03	Mt Washington: Summit	1895	44.27049	-71.30483	Block	2.0	149200 ± 8200	156100 ± 8330	152600 ± 5840	6.26 ± 0.16	12710 ± 2770
PTMW-04	Mt Washington: Tuckermans Ravine	1326	44.26149	-71.29511	Block	1.0	12590 ± 1140	12590 ± 700	12590 ± 600	6.76 ± 0.55	
PTK-06	Baxter Peak, Katahdin Summit	1606	45.90422	-68.92161	Bedrock	4.0	9280 ± 600	9860 ± 540	9600 ± 400	6.36 ± 0.32	
PTK-07	Baxter Peak, Katahdin Summit	1607	45.90471	-68.92191	Block	4.0	37260 ± 2070	34310 ± 1770	35560 ± 1350	7.29 ± 0.23	11040 ± 2190

*Ages calculated from Lal/Stone scaling scheme using CRONUS (Balco et al., 2008) assuming no geomagnetic correction and assuming northeastern North American production rate (Balco et al., 2009). Uncertainty is external error from CRONUS (Balco et al., 2008). CRONUS considers different standards used to normalize isotope ratio measurements. Topographic sheilding was negligable for all samples.

#Assuming production rate of 12.7 ± 1.1 atoms/(g*yr) and Lal/Stone scaling scheme

@^{26}Al/^{10}Be ratio calculated by CRONUS and normalized to accepted value of AMS standards per Nishiizumi et al., 2007

Table S2. Isotopic Measurements, New England Summits

Sample Name	Location	Type	Latitude (°N)	Longitude (°E)	Elevation (m)	Thickness (cm)	Quartz Mass (g)	Be Carrier (g)*	Al Carrier (g)*	Measured Total Al (ug)**	Measured $^{10}Be/^{9}Be$ Ratio***	$^{10}Be/^{9}Be$ Ratio Unc.	Measured $^{26}Al/^{27}Al$ Ratio***	$^{26}Al/^{27}Al$ Ratio Unc.	^{10}Be Conc. (atoms g^{-1})	^{10}Be Unc. (atoms g^{-1})	^{26}Al Conc. (atoms g^{-1})	^{26}Al Unc. (atoms g^{-1})	Measured $^{26}Al/^{10}Be$****	Measured $^{26}Al/^{10}Be$ Unc.
PTD94-19	Franconia Ridge	Bedrock	44.13620	-71.64402	1575	3.0	39.230	0.252	0.000	7579	2.303E-12	6.049E-14	1.321E-12	2.674E-14	9.782E+05	2.599E+04	5.696E+06	1.154E+05	5.82	0.19
PTD94-20	Mt. Washington	Block	44.26982	-71.30483	1896	3.0	25.360	0.253	0.000	27732	6.139E-13	1.439E-14	9.134E-14	6.745E-15	3.933E+05	9.717E+03	2.224E+06	1.647E+05	5.66	0.44
PTD94-21	Mt. Washington	Block	44.27004	-71.30483	1896	3.0	41.320	0.251	0.000	7724	9.452E-13	2.187E-14	5.396E-13	1.566E-14	3.739E+05	8.929E+03	2.248E+06	6.541E+04	6.01	0.23
PTMW-01	Mt. Washington	Block	44.27049	-71.30483	1896	1.0	26.650	0.254	0.000	15620	9.611E-13	2.256E-14	2.431E-13	1.141E-14	5.969E+05	1.444E+04	3.175E+06	1.493E+05	5.32	0.28
PTMW-02	Mt. Washington	Block	44.27049	-71.30483	1896	3.0	30.890	0.355	0.000	29769	1.905E-12	3.652E-14	4.132E-13	1.019E-14	1.450E+06	2.808E+04	8.884E+06	2.193E+05	6.13	0.19
PTMW-03	Mt. Washington	Block	44.27049	-71.30483	1895	2.0	39.409	0.253	0.576	3229	7.524E-12	1.372E-13	9.528E-12	1.661E-13	3.218E+06	5.888E+04	1.742E+07	3.039E+05	5.41	0.14
PTMW-04	Mt. Washington	Block	44.26149	-71.29511	1326	1.0	40.228	0.355	0.000	20341	3.168E-13	7.961E-15	9.184E-14	6.976E-15	1.767E+05	4.796E+03	1.033E+06	7.878E+04	5.85	0.47
PTK-06	Mt. Katahdin	Bedrock	45.90422	-68.92161	1606	4.0	39.915	0.254	0.000	7106	4.330E-13	1.017E-14	2.416E-13	1.034E-14	1.739E+05	4.438E+03	9.565E+05	4.118E+04	5.50	0.28
PTK-07	Mt. Katahdin	Block	45.90471	-68.92191	1607	4.0	40.730	0.254	0.000	7060	1.364E-12	2.317E-14	9.809E-13	2.541E-14	5.584E+05	9.706E+03	3.792E+06	9.835E+04	6.79	0.21

*Be and Al carriers added to samples both had a concentration of 1000 ppm.
**Refers to the total Al in the sample (including both native Al in quartz and Al added via carrier, if applicable) quantified in duplicate by ICP-OES directly following digestion.
***During AMS analysis, all Be samples were normalized to standard LLNL3000 (except sample PTK-07, which was normalized to LLNL 1000) and all Al samples were normalized to standard KNSTD9919.
****Ratio considering accepted value of standards at time of measurement

Table S3: In situ ^{14}C sample analytical data

Sample Name	Lab Number	AMS Number	Mass Quartz *(g)*	V_{CO2} *(mL)*	V_{dil} *(mL)*	F_M	$[^{14}C]$ 10^5 *at g^{-1}*
PTDK-7	RN-785	AA-54556	4.9975	0.0137 ± 0.0011	2.1115 ± 0.0203	0.0271 ± 0.0006	3.3534 ± 0.1130
PTMW-3	RN-786	AA-54557	5.0069	0.0443 ± 0.001	1.3774 ± 0.0131	0.0527 ± 0.0007	4.3015 ± 0.1036

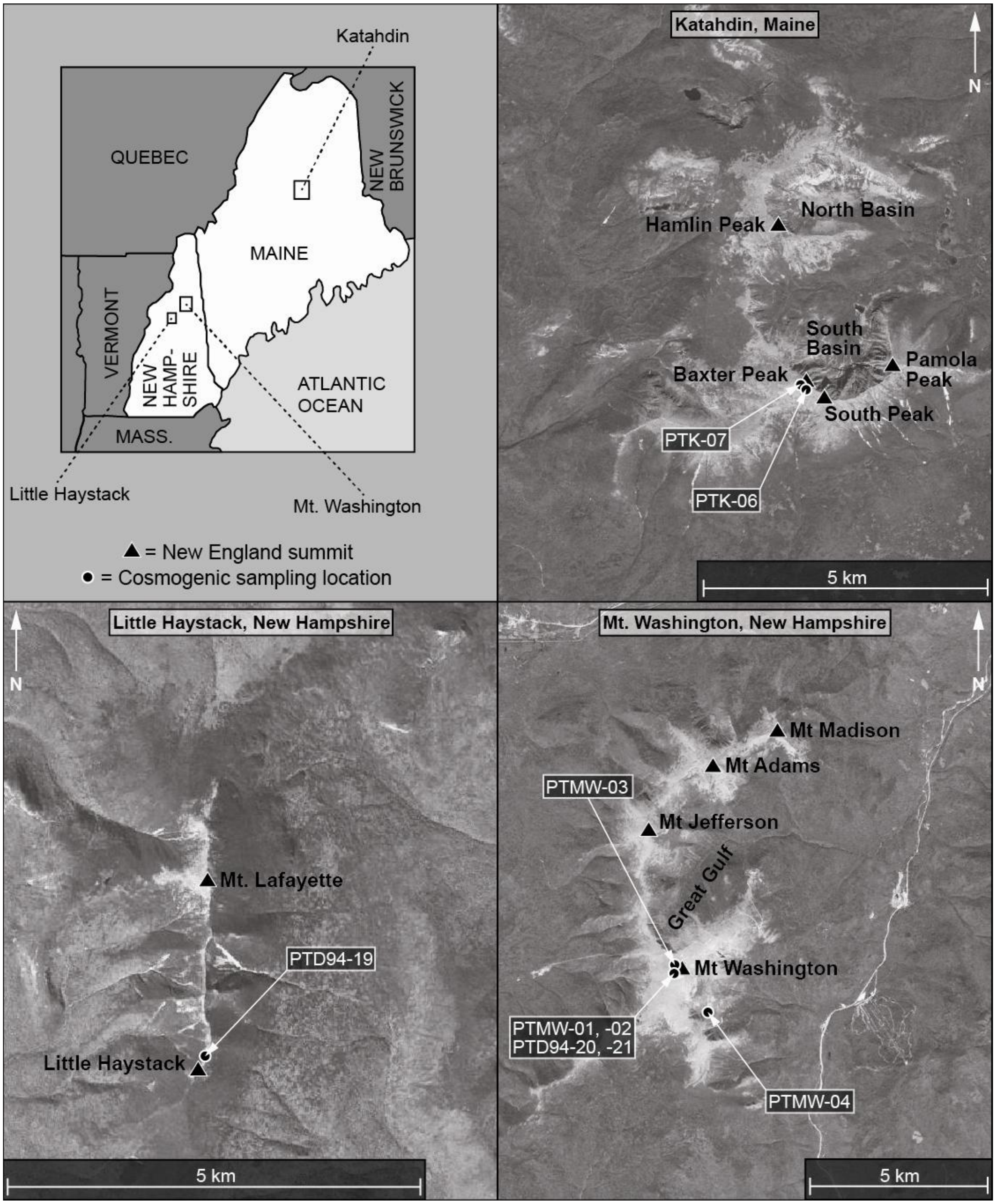
Notes: $\delta^{13}C$ of both diluted samples assumed to be -35.0 ± 2.0 ‰ (typical value for diluted samples). Uncertainty in quartz mass: ± 0.0002 g. Fraction modern (F_M) values corrected per Hippe and Lifton (2014). Concentration calculated after subtracting long-term extraction system process blank of $(1.2367 \pm 0.3531) \times 10^5$ ^{14}C at.

Table S4. Selected radiocarbon ages older than Last Glacial Maximum from New England

Site Name	Latitude (°N)	Longitude (°W)	^{14}C Age (yr BP)	Lab Number	Material	Calibrated Age (ka BP)[a]	Original Reference
Gould Pond	44 59 33	69 19 09	25280±1010	SI-5372	Marine Shells	29040 (27106-31083)	Anderson et al., 1992
Isie Lake	47 04 15	68 39 23	24300±110	OS-6435	paleosol	28340 (28020-28652)	Dorion, 1997
Jo Mary Pond	45 34 38	68 02 19	24500±130	OS-3170	paleosol	28550 (28208-28829)	Dorion, 1997
Upper South Branch Pond	46 05 00	68 54 00	29200±550	SI-4519	wood	33240 (31763-34275)	Anderson et al., 1986

[a]Age estimates include the median intercept and the minimum and maximum ages in parentheses based on 2 standard deviations from minimum and maximum intercepts using CALIB 7.0 (Reimer et al., 2014) and considering combined IntCal04/Marine04

7. Maps of sampling sites



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