NEW VIEWS ON THE DEGLACIATION OF MT MANSFIELD

By

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INTRODUCTION

Mt. Mansfield, the highest peak in Vermont, preserves evidence of Pleistocene glaciation including erratic boulders, striations, and ice-sculpted rock outcrops. Over the past several years, we have been collecting samples of bedrock and erratic boulders and using them for cosmogenic dating. Mapping of recessional sedimentary features including moraines and striations where bedrock crops out on the mountain, place these data in context. This part-day day trip will (weather permitting) travel to the top of the mountain by car and visit locations we have sampled while discussing the ages that resulted from these analyses. We will discuss evidence for ineffective erosion at the mountain peak (could there have been cold-based ice?). If time permits, we may examine ice marginal deposits in the valley resulting from ice channelized by the topography. For those who are interested, the trip will end with a tour of the Vermont cosmogenic clean labs now supported by as a community sample processing facility by the US NSF.

SETTING

Mt. Mansfield (Figs. 1 and 2, elevation 1339 m a.s.l.) is Vermont's highest peak, located in the north-central part of the state, along the spine of the Green Mountains. Mt. Mansfield is ~35 km east of the Champlain valley and ~100 km west of the Connecticut River valley. The study area is underlain by rocks that contain sufficient quartz for analysis of *in situ* cosmogenic nuclides. The landscape in the study area is subalpine and alpine, dominated by conifers, with the highest elevations just above tree line. Following deglaciation, the summit has served as a high-elevation refuge for plants that still persist in the warmer modern climate and grow in alpine soils (Munroe et al., 2007).

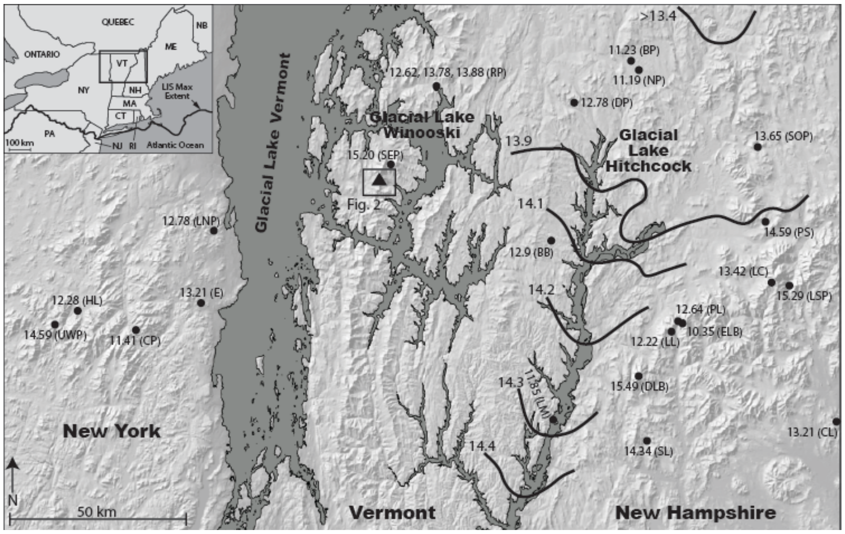

Figure 1. Generalized map of northern New York, Vermont, and New Hampshire showing previous age constraints (in ka) relevant to Mt. Mansfield's deglacial history. Ice margin positions based on glacial Lake Hitchcock varve chronology from Ridge et al. (2012) shown as thick black lines. Radiocarbon ages shown with black circles. Extent of glacial lakes are shown in light gray. Black box shows location of Figure 2. Mt. Mansfield is shown by the black triangle. Inset shows location of the study area.

Field observation reveals evidence of prior glaciation. Striations are visible on many bedrock surfaces and show multiple directions of ice flow including NW-SE along most of Mt. Mansfield's summit ridge, N-S in some lower elevation areas, and W-E in the valley south of Mt. Mansfield (Fig. 2). At lower elevations, bedrock outcrops are rounded and sculpted; however, at higher elevations, outcrops sometimes exhibit frost shattering. In areas where the mountain slopes are mantled by thick accumulations of till, such till frequently forms distinct step-like moraines (Fig. 2). Recent mapping has confirmed that these features are not cored by bedrock and do not show signs of mass movement (Wright, 2018). Continuous parallel flights of moraines are clearly visible on the LIDAR imagery where they gently slope into tributary valleys, with spacing between adjacent moraines typically ranging between 20 and 75 m.

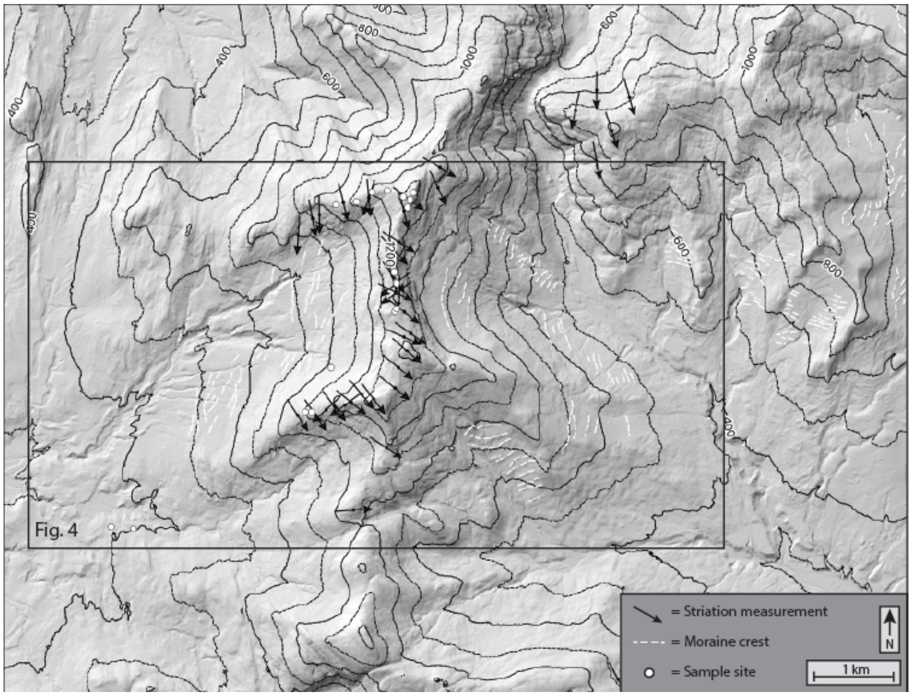

Figure 2. Shaded relief map of the Mt. Mansfield area based on LIDAR, with 100 m contours shown in black (LIDAR from the Vermont Center for Geographic Information, www.vcgi.vermont.gov). Thin arrows denote striation measurements and white dashed lines show mapped moraine crests. Sample sites are shown with white circles (refer to Figure 3 for sample names).

PREVIOUS WORK

Mt. Mansfield has long been the subject of geologic inquiry, beginning with the work of Hitchcock et al. (1861). The occurrence of glacial striations (Hungerford, 1868) and erratic boulders on the summit ridge (Christman, 1959; Hitchcock et al., 1861) provided the initial evidence that even the highest elevations had been covered by a large, continental-scale ice sheet. While some postulated that large sediment ridges on Mt. Mansfield's east side were end moraines formed by an episode of cirque glaciation that post-dated regional glaciation (Wagner, 1970), others argued that steep valleys on the mountainside were formed prior to the LGM (Davis, 1999; Loso et al., 1998; Waitt and Davis, 1988) and that the ridges originally interpreted as end moraines of cirque glaciers near Mt. Mansfield were instead eskers formed beneath the retreating ice sheet (Wright et al., 1997).

The timing of deglaciation of the summit region was unknown prior to recent cosmogenic dating reported here. The only nearby age data come from Sterling Pond (SEP) ~4 km northeast of the summit and ~400 m lower in elevation (Fig. 1). Here, an organic radiocarbon measurement (hereafter organic ^{14}C, to differentiate from *in situ* ^{14}C) from bulk sediment at the base of a core yielded an age of 12760 ± 70 ^{14}C yr BP (Lin, 1996), or 15100-15300 cal yr BP (1σ age range, all organic ^{14}C ages have been recalibrated using Calib version 7.1 (Stuiver et al., 2015) and the IntCal13 calibration curve (Reimer et al., 2013)). This age, if correct, is a minimum limit for the timing of summit deglaciation because it is considerably lower in elevation (919 m) than the summit (1339 m) and would have still been buried by ice after Mt. Mansfield's summit became exposed as the ice thinned. However, bulk lake sediment organic ^{14}C ages may be inaccurate. On one hand, there is an unknown lag time needed for vegetation to become established and organic material enter the lake basin (Davis and Davis, 1980); on the other hand, bulk lake sediment ages are often too old because they contain recycled carbon (Davis et al., 1995) or are subject to hard water effects (Shotton, 1972). Several studies in Vermont have shown organic macrofossil ages to be hundreds of years younger than bulk sediment ages (Brown, 1999; Noren, 2002; Parris, 2003), likely because of carbon recycling and the sinking of macrofossils through unconsolidated pond-bottom material.

Chronologic data from the glacial lake valleys to the west and east of Mt. Mansfield (Ridge, 2004) provide context for the deglaciation of the study area. Because lakes in these valleys did not form until the valleys became ice-free, ages from the glacial lake sediments provide minimum limits for the deglaciation of Mt. Mansfield. To the west, the Champlain valley (Fig. 1) contained glacial Lake Vermont (Chapman, 1937; Rayburn et al., 2005; Ridge, 2004). Macrofossils from glacial Lake Vermont sediments have organic ^{14}C ages of 10900 ± 75 ^{14}C yr BP (Rayburn et al., 2007) and 11360 ± 115 ^{14}C yr BP (Cadwell et al., 1991; Rayburn et al., 2007), yielding calibrated ages of 12710-12830 and 13100-13300 cal yr BP respectively (1σ age ranges). To the east, varve chronologies from glacial Lake Hitchcock sediments in the Connecticut River valley (Fig. 1) place the retreating LIS margin at the same latitude as Mt. Mansfield after 13900 cal yr BP (Ridge et al., 2012), following abandonment of the Littleton-Bethlehem moraine in northern New Hampshire (Thompson et al., 2017). Along the eastern border of the Green Mountains, varves from glacial Lake Winooski (Larsen, 1972, 1987), when correlated with the North American Varve Chronology (Ridge et al., 2012), indicate that the lake existed from ~14100 to 13820 cal yr BP (Larsen et al., 2003; Wright, 2018). The formation of Lake Winooski at ~14100 cal yr BP represents the most geographically proximal minimum limit for the deglaciation of Mt. Mansfield as constrained by glacial lakes.

In addition to information from glacial lakes, basal organic ^{14}C ages from sediment cores of small, upland lakes and ponds in the northern half of Vermont, northeastern New York, and northern New Hampshire (Fig. 1) provide additional constraints for the timing of deglaciation (Ridge et al., 1999). However, due to the uncertainties discussed above, particularly the recycling of old carbon in bulk sediments (Davis et al., 1995) and the unknown lag time between deglaciation and organic sedimentation (Davis and Davis, 1980), basal sediment core ages vary widely. Ages from material at the bottoms of lake sediment cores range from 13000 to 9155 ^{14}C yr BP (Bierman et al., 1997; Davis et al., 1980; Lin, 1996; McDowell et al., 1971; Munroe, 2012; Noren et al., 2002; Parris et al., 2010; Rogers et al., 2009; Spear, 1989; Spear et al., 1994; Sperling et al., 1989; Thompson et al., 1996; Whitehead and Jackson, 1990), yielding calibrated ages of 15490-10350 yr BP (Fig. 1). Compilations of radiocarbon ages from the northeastern United States, including those from New York, Vermont, New Hampshire, Massachusetts, and Maine, show a similarly wide spread of ages (Davis and Jacobson, 1985; Gaudreau and Webb, 1985).

METHODS

We collected samples during 2015-2017 from 20 bedrock and boulder surfaces using a hammer and chisel. Samples span from 411 to 1305 m a.s.l. and are from Mt. Mansfield's lowlands, ridges, and summit. We avoided sampling surfaces that exhibited evidence of significant subaerial erosion and boulders that may have rolled. At each sample site, we used high-precision GPS to record latitude, longitude, and elevation; we measured thickness and shielding, and made observations about sample surface characteristics. We isolated quartz for *in situ* ^{10}Be and ^{14}C analyses at University of Vermont following the methods of Kohl and Nishiizumi (1992).

We calculated ^{10}Be and ^{14}C exposure ages with Version 3 of the online exposure age calculator formerly known as CRONUS Earth (Balco et al., 2008) and the regionally-calibrated northeastern North American production rate dataset (Balco et al., 2009). We implement "LSDn" scaling because it uses nuclide-specific equations that reflect the differences between ^{10}Be and ^{14}C production (Borchers et al., 2016; Lifton, 2016; Lifton et al., 2014). The calculated ages assume no nuclides inherited from previous exposure and no post-exposure erosion or shielding.

AGE DATA

Background-corrected sample ^{10}Be concentrations yield exposure ages of 12.9 ± 0.4 to 22.9 ± 0.5 ka (1σ analytical uncertainties, Figs. 3 and 4). In the one instance where we sampled bedrock (MM-02, 14.8 ± 0.3 ka) and boulder (MM-01, 14.5 ± 0.3 ka) surfaces in close proximity (at 1170 m a.s.l.), the two ages agree within 1σ internal uncertainties (Fig. 3). In general, exposure ages increase with elevation (Fig. 4); samples below ~1200 m a.s.l. form

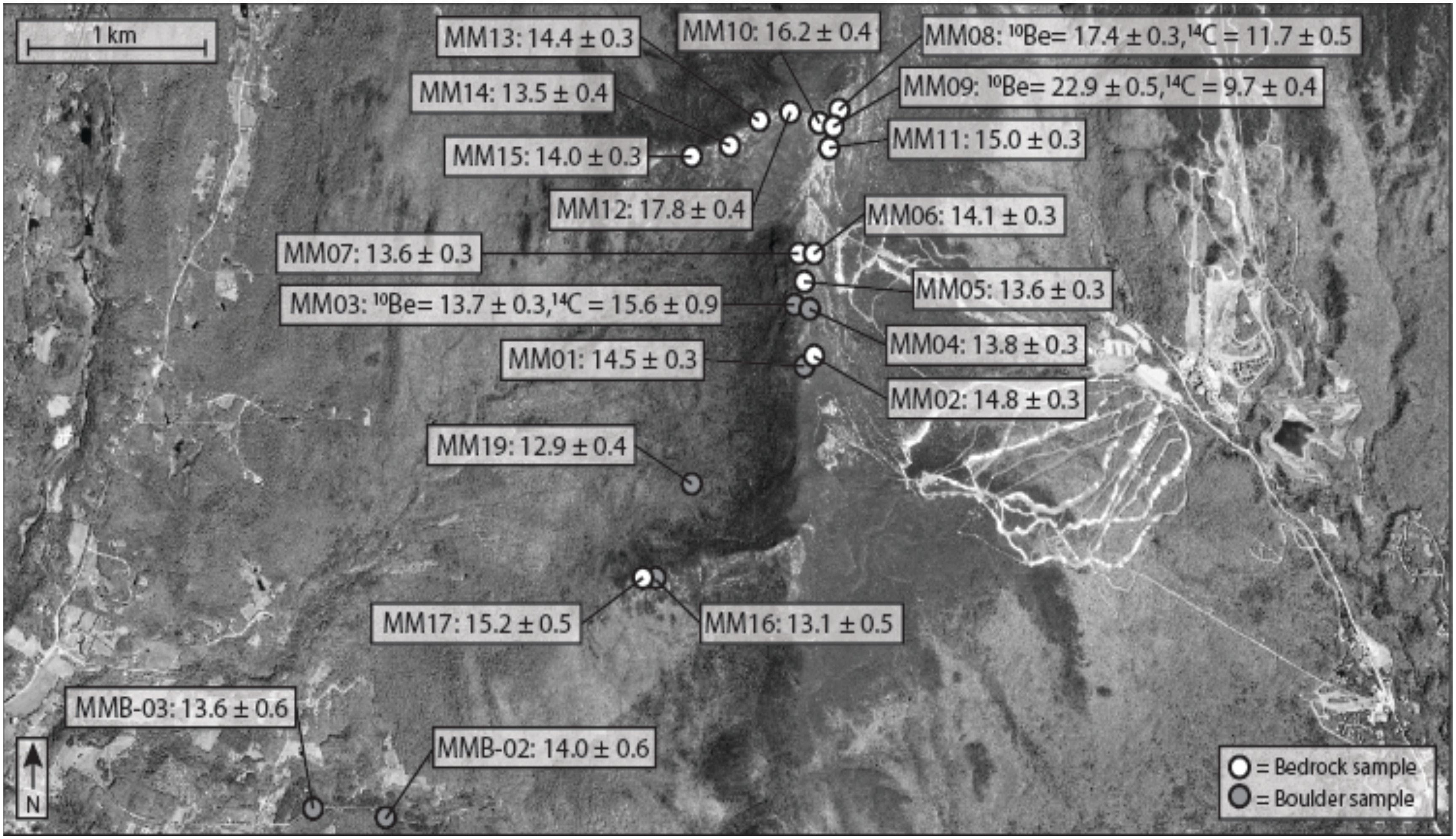

Figure 3. Satellite imagery (Google Earth) of the Mt. Mansfield area (see location context in Figs. 1 and 2). Sample locations are shown with white circles (bedrock) and gray circles (boulders). All ages in ka are ^{10}Be unless otherwise specified; uncertainties are 1σ internal (analytical).

an overlapping population of ages (average 13.9 ± 0.6 ka, n = 15, 1SD) and samples above ~1200 m a.s.l. are older (15.0-22.9 ka).

Background-corrected in situ ^{14}C concentrations yield exposure ages of 9.7 – 15.6 ka (Figs. 3 and 4). For the lower-elevation boulder sample (MM-03, 1176 m a.s.l.), the ^{10}Be (13.7 ± 1.2 ka) and *in situ* ^{14}C (15.6 ± 2.5 ka) ages agree within 1σ external uncertainties (Fig. 3; we use external uncertainties here because of the differing production rate calibrations and scaling). Conversely, closer to the summit, in samples of bedrock, there are significant mismatches between the exposure ages generated with the two nuclides (MM-08, ^{10}Be 17.4 ± 1.5 ka, ^{14}C 11.7 ± 1.4 ka; and MM-09, ^{10}Be 22.9 ± 2.0 ka, ^{14}C 9.7 ± 1.0 ka). The ^{14}C ages are younger.

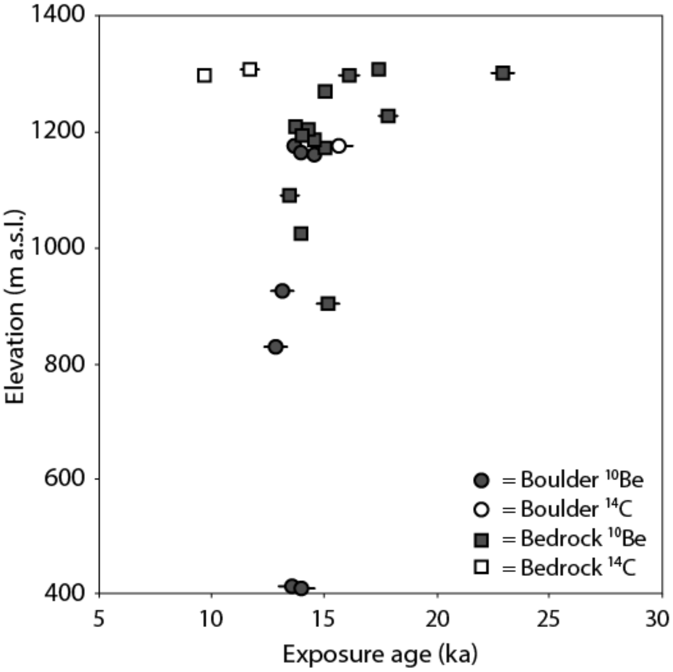

Figure 4. Exposure ages (calculated assuming no inherited nuclides and no post-burial shielding or erosion) shown against elevation. Round symbols show boulders and square symbols show bedrock; gray symbols show ^{10}Be and hollow symbols show *in situ* ^{14}C. Error bars show 1σ internal uncertainties, which in many cases are smaller than the symbols.

INTERPRETATION

Mt Mansfield's lower elevations (~400-1200 m a.s.l.) were deeply eroded by the LIS, yielding fresh, glacially sculpted landscapes following deglaciation. This erosion is evidenced by the agreement between bedrock and boulder exposure ages and is also suggested by the agreement between exposure ages generated with different nuclides on the same sample surface (Figs. 3 and 4). The agreement between ^{10}Be and ^{14}C ages indicates that at least several meters of rock were removed from exposed surfaces during the last glaciation, leaving behind minimal inherited ^{10}Be (the longer-lived nuclide) from pre-LGM exposure. The exposure ages at lower elevations therefore record the timing of exposure and yield an estimate of deglaciation at ~13.9 ± 0.6 ka (^{10}Be, n = 15, average, 1SD).

Data from Mt. Mansfield's uplands demonstrate that the geomorphic history at high elevations is more complicated than at lower elevations. The presence of two young *in situ* ^{14}C ages (11.7 and 9.7 ka, both from surfaces with older ^{10}Be ages) suggests that Mt. Mansfield's summit was shielded by ice, snow, and/or till for longer than lower elevation areas. These young exposure ages (as compared to the ~13.9 ka exposure ages at lower elevations) imply that bedrock surfaces at the highest elevations were isolated from nuclide production until several ka after the LIS margin had retreated from the region. The close agreement between ^{10}Be and *in situ* ^{14}C exposure ages at a lower elevation site (sample MM-03) suggests that prolonged shielding was restricted to the summit region.

Post deglaciation shielding of samples collected from Mt. Mansfield's summit could be the result of one or more sheilding processes, including cover by thick snow, stagnant ice, and/or till. In the case of ice or snow, small snowfields or carapaces could have remained behind following rapid LIS thinning (although this is unlikely given how rapidly the ice sheet was losing mass at that time, Lambeck et al. (2014)) or could have regenerated. In the case of till, sediment cover could have existed for millennia following deglaciation, eventually eroding away to expose bedrock surfaces. Although there is abundant till on Mt. Mansfield's flanks, there is virtually no till on the summit today, so it was either never there or has been completely removed. Regardless of the shielding mechanism, the summit surfaces were ultimately exposed in the early Holocene (Figure 5), perhaps driven by regional warming also observed in paleoenvironmental proxies in nearby Sterling Pond (Lin, 1996), Nulhegan Pond, and Beecher Pond (Fig. 1; Munroe (2012)). If exposure of the summit occurred gradually, through slow melting of ice/snow or progressive stripping of till, then the bedrock surfaces we analyzed would have received a portion of their nuclide concentrations through thin cover and partial shielding; in that case, the *in situ* ^{14}Cages represent maximum limits for the time at which bedrock surfaces became bare.

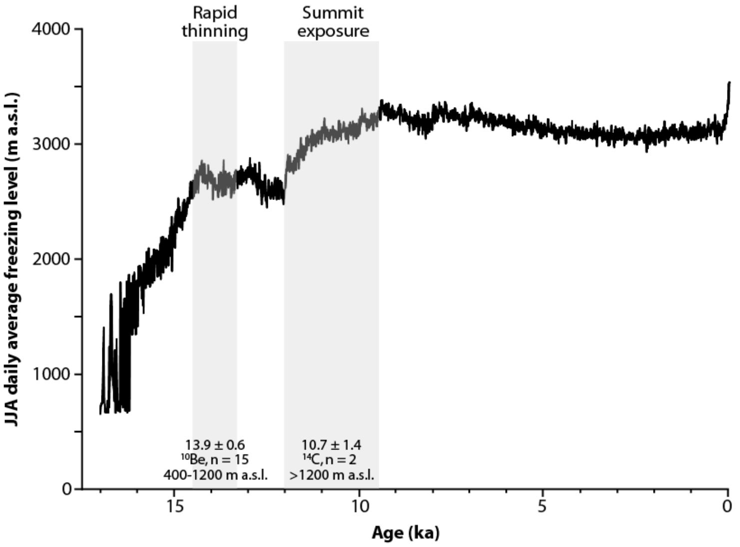

Figure 5. Simulated June/July/August daily average freezing level for 44°N 72°W from Liu et al. (2009), courtesy of F. He. Overlain in gray bars are inferences from the cosmogenic data described in the text.

Assuming the *in situ* ^{14}C ages record the time of exposure of Mt. Mansfield's summit, then the ^{10}Be concentrations must contain a large inventory of nuclides inherited from pre-LGM exposure (because ^{10}Be is the longer-lived nuclide and decay during LGM burial was negligible). In that case, assuming an exposure time of 10.7 ka (the average of the two summit *in situ* ^{14}C ages), the high-elevation surfaces are carrying an excess of ~4-12 ka of ^{10}Be, or ~30-50% of their total nuclide concentrations. These old ^{10}Be exposure ages do not represent early thinning of the LIS and exposure of Mt. Mansfield's summit at ~23 ka (the exposure ^{10}Be age of bedrock surface MM-09) because the young *in situ* ^{14}Cages preclude this possibility and because the ice margin was at its terminal position several hundred km south of the study area at that time (Balco et al., 2002; Corbett et al., 2017). Further, the heterogeneity of the high-elevation ^{10}Be exposure ages is more indicative of variable sub-glacial erosion, which often creates a scattered population of ages (Briner et al., 2005), instead of early exposure, which would result in a single population of older exposure ages.

Significant inherited ^{10}Be from pre-LGM exposure could persist in Mt. Mansfield's high elevations due to cold-based ice with limited erosive power (Kleman and Borgstrom, 1994) covering Vermont's highest topography and/or because the duration of ice flow over the summit was very short. The existence of cold-based Laurentide ice has been documented widely in the high latitudes (Briner et al., 2014; Briner et al., 2006; Corbett et al., 2016;

Margreth et al., 2016) and also in the contiguous United States, including the low elevations of Wisconsin (Bierman et al., 1999; Colgan et al., 2002) and the highest summits of Maine and New Hampshire (Bierman et al., 2015). In this case, the summit regions of Mt. Mansfield (and other mountains of the northeastern United States) may represent relict landscapes that were preserved, but not deeply eroded or reshaped, beneath LGM ice cover (Sugden, 1977, 1978; Sugden and Watts, 1977). The soils on the summit of Mt. Mansfield, which preserve evidence of significant contribution from dust (Munroe et al., 2007), may predate the Holocene if they were preserved subglacially. The presence of old, long-exposed soils is consistent with the observation that sediments from the Brown's River, which drains Mt. Mansfield's western flank, have appreciably higher meteoric ^{10}Be concentrations than other river sediments in Vermont (Borg, 2010).

ROAD LOG

The trip begins at the Stowe Mountain Resort parking lot; this is adjacent to the Toll Road up Mount Mansfield and reached from the Mountain Road (Route 108) in Stowe, VT. It is immediately adjacent to the Inn at the Mountain (https://earth.app.goo.gl/p4hZ95) and located at: 44.51069951, -72.76578428. We will consolidate vehicles (primarily using UVM vans) to reduce impact on the Mountain Road and because of limited parking at the summit. Trip limited to 30 people in total. NOTE: you must bring lunch, food, water and warm clothes; once we leave the parking lot there are no facilities on the mountain. The road is only open in the summer to vehicles and there is a charge for use. In the winter, it is used as a ski trail.

Start of driving trip, Toll Road, Mile 0 – Parking lot off of 108 at the base of the Toll Road. From here we will drive 4.8 miles up a steep, one lane, mostly dirt road.

End of driving trip, Toll Road, Mile 4.8 – Arrive at the parking lot at top of the road, elevation 1170 m asl. From here, we will walk along the ridge, weather permitting to a variety of sampled outcrops on the summit ridge trail. The trail is rough and rocky and not always well marked. Our journey and time spent on the ridge will depend on the weather which can be quite variable and potentially dangerous any time of year. The summit of Mt. Mansfield is 1339 m and about a 2 km walk each direction from the upper parking lot. We hope to be able to walk to the summit and return if the weather allows.

Since our route will depend on weather, we include below a table of GPS coordinates for sample sites allowing others to relocate within a meter of where we collected each sample.

Table 1. Cosmogenic Sample Locations and Types

Sample	Latitude	Longitude	Elevation (m)	Category
MM-01	44.530322	-72.817178	1164	Boulder
MM-02	44.530622	-72.816911	1172	Bedrock
MM-03	44.533573	-72.816966	1176	Boulder
MM-04	44.533473	-72.816888	1174	Boulder
MM-05	44.534746	-72.817298	1180	Bedrock
MM-06	44.536081	-72.817325	1197	Bedrock
MM-07	44.536076	-72.817382	1197	Bedrock
MM-08	44.543693	-72.814341	1305	Bedrock
MM-09	44.542895	-72.814863	1300	Bedrock
MM-10	44.543201	-72.815912	1297	Bedrock
MM-11	44.542003	-72.815257	1270	Bedrock
MM-12	44.543891	-72.818372	1226	Bedrock

MM-13	44.543708	-72.820781	1174	Bedrock
MM-14	44.542637	-72.823174	1090	Bedrock
MM-15	44.542317	-72.826389	1025	Bedrock

Stop 1. Sample sites MM-01 and MM-02. This is a site where a boulder and a nearby bedrock outcrop were collected. Both return ^{10}Be exposure ages that are similar within error of 14.5 and 14.8 ka, respectively. We will speak at this location about sampling strategy, the use of high precision GPS for sample location, and the utility of matched boulder/bedrock pairs to test for inherited nuclides.

Stop 2. Sample site MM-03. This erratic boulder has been known to science for nearly two centuries. Featured in the illustration pictured first Edward Hitchcock's *Report on the Geology of Vermont* (1861) and reproduced below along with Thom Davis's best vintage interpreation, it has a ^{10}Be exposure age of 13.65 ka and a ^{14}C exposure age that is older but within one standard deviation (15.6 ka). We will speak at this boulder about the implications of the dual isotope measurements for ice cover and deglacial history. Note that a nearby boulder (MM-04, 15 m away) gives a nearly identical ^{10}Be age of 13.75 ka.

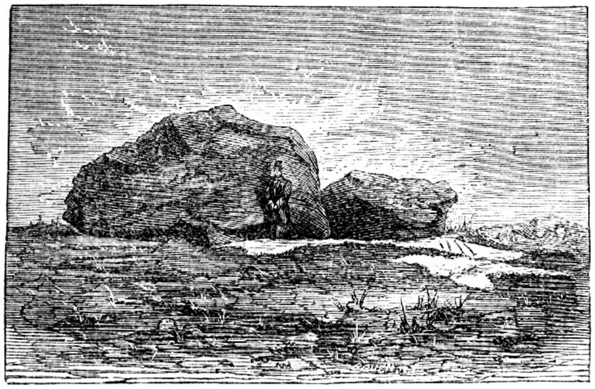

Figure 6. Sample site MM-03, then (1861) and now (2016).

Stop 3. MM-06 and -07. These are two bedrock samples collected very close to one another as a test of reproducibility. They have ^{10}Be exposure ages of 14.1 and 13.6 ka. We will examine these sites closely and compare the weathering to that of the sites near the peak (Stop 4) which have higher, in some cases much higher ^{10}Be exposure ages.

Stop 4. Sample sites MM-08, -09, -10, and -11. These are four bedrock samples sites near the summit of Mt. Mansfield ranging in elevation from 1270 to 1300 m asl. They have 4 of the 5 oldest exposure ages (15.2 – 22.9 ka) that we have measured on the mountain (the other being MM-12 on Sunset Ridge, about 50 m lower). These relatively high ^{10}Be exposure ages imply ineffective glacial erosion and the inheriance of some nuclides from a prior period of surface or near-surface exposure. Two of the samples, MM-08 and MM-09 have also have in situ ^{14}C exposure ages. These ages are much younger, 11.7 and 9.7 ka, respectively. We will talk at these sites about the need for some type of cover being present on the summit (till, ice, snow fields) after deglaciaion of the lower flanks of Mt. Mansfield at 13.9 ± 0.6 ka. After this stop, we will return to the vehicles and descend the Toll Road.

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