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New Evidence of a Post-Laurentide Local Cirque Glacier on Mount Washington, New Hampshire

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NEW EVIDENCE OF A POST-LAURENTIDE LOCAL CIRQUE GLACIER ON MOUNT WASHINGTON, NEW HAMPSHIRE

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Abstract

As global temperatures warmed and the last North American continental ice sheet receded there were several climate reversals during which time mean temperatures in New England were significantly reduced. Decreased temperatures in combination with increased precipitation may have supported the formation or reactivation of local mountain glaciers in pre-existing cirques on Mt. Washington, New Hampshire. Evidence supporting the existence of a local cirque glacier would provide important constraints on climatic conditions during the late-glacial Pleistocene transition. Preliminary mapping done in the area has identified a potential terminal moraine associated with a local valley glacier in the Great Gulf, the largest cirque on Mount Washington. The presence of this deposit is significant because any pre-Wisconsin evidence of valley glaciers in the Great Gulf would likely have been expunged by the presence of continental ice.

In order to determine the origins of the possible moraine, representative samples of the till were collected by digging five test pits across the feature, sampling ~50 hand-sized stones from each pit, and determining the provenance of individual stones. Results indicate that the landform is composed of unsorted clasts with provenances of both local and regional origin. Clasts sourced within the Great Gulf support the interpretation that they were deposited by processes dependent on the presence of a local mountain glacier during a post-Wisconsin climate reversal. Stones of more distant origins may be attributed to residual till, associated with a continental ice mass that occupied the cirque at the time of local glacier reactivation. These data show that the landform was deposited from glacial processes taking place within the Great Gulf, and the pronounced topography and volume of the landform would support its interpretation as a terminal moraine.

By reconstructing the glacier using the feature as the terminus, a paleo-ELA was calculated and climate conditions necessary to promote the growth of an icemass were ascertained. This ELA represents the altitude at which the mean annual isotherm at which the climate is considered suitable to support an icemass. Comparing this climate to the contemporary allows us to evaluate the magnitude of late-Pleistocene climate reversals in the White Mountains. A paleo-ELA of ≈850m was calculated and the contemporary climate at that altitude was 6-8°C warmer than the minimum conditions necessary for a glacier to exist with no significant increase in precipitation. This tells us that if a glacier did occupy the cirque after the recession of the continental ice sheet, the late-Pleistocene was a little colder/wetter than previously thought in the White Mountain region of New Hampshire.

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Introduction

1.1 Introduction

The Presidential Range in New Hampshire provides geologists with a diverse landscape ranging from deep-cut glacial valleys to pristine alpine zones atop New England's highest peaks. The range is one of the only places in New England that has evidence of both continental glaciers, as seen by the spectacular notches cut through the mountains and widespread drift deposits, and local alpine glaciations as evident by the numerous cirques carved out from the sides of mountains. Since the first researchers began examining this landscape, it was known that ice, at one time, must have carved out these cirques; however the timing of such an event has been a subject of much controversy. The region was also overrun by the Laurentide ice sheet associated with the Last Glacial Maximum (LGM) and withdrew between 12,500 ± 350 and 11,900 ± 70 cal ^{14}C years BP (Thompson et al., 1999), but it is unknown whether alpine glaciations may have been reactivated during the subsequent interglacial period or if features predating the last glacial maximum (LGM) may have persisted.

For almost a century the search for evidence of post-Wisconsinan local alpine glaciations has continued (Goldthwait, 1913). The absence of terminal moraines in the cirques in the area is often cited as the most important evidence for cirque glaciations preceding the last continental glaciations (Goldthwait, 1913; Antevs, 1932; Goldthwait, 1970; Davis, 1999), while others argue that the moraines do not necessarily have to be present (Johnson, 1933), or they have yet to be found (Bradley, 1981; Fowler, 1984).

However, new evidence below the Great Gulf cirque complex (Figure 1,2) may elucidate the timing of local cirque glaciations relative to the LGM. A topographically pronounced feature composed of unsorted sediments below the Great Gulf cirque was identified by Fowler (2011) as a terminal moraine. A terminal moraine at the valley floor associated with the cirque system could imply that there was an alpine glacier present after the last continental ice sheet had receded from the valley. Any feature associated with cirque activity would have been expunged as the continental ice sheet moved through the valley. However, the moraine could also be associated with the ice sheet itself readvancing down the valley after its initial retreat from the area. In order to determine the origins of the feature, an analysis of the till that makes up the feature was performed; if the provenance of the till clasts indicated that they are of cirque origin, then they could have been deposited by an alpine glacier in the Great Gulf cirque complex.

The presence of a local alpine glacier after the retreat of the continental ice sheet would provide insights into the late-Pleistocene climate history of the White Mountains and New England. A reactivation of an alpine glacier during an interstadial cooling period after the recession of the continental ice sheet would mean the impact of an abrupt climate reversal, such as the Younger Dryas or Older Dryas, was significant enough facilitate the growth of a glacier. Such evidence would provide us with a proxy for the climate conditions of the White Mountains after the LGM because glaciers can only exist under a limited range of temperature and precipitation conditions.

The question remains as to whether the proposed moraine can be associated with an alpine glacier or a continental ice sheet. In order to evaluate the origin of the landform, a provenance analysis of the till composing the feature, as well as a morphometric analysis of the cirque and a numerical reconstruction of a former ice mass capable of depositing such a feature, must be done. If the feature is determined to have originated from an alpine glacier occupying the Great Gulf cirque, it may reflect the reactivation of a local cirque glacier after the recession of the continental ice sheet, and that the climate after the recession of the ice sheet must have undergone a reversal with a magnitude capable of reactivating an ice mass. To determine the source of sediments composing the feature, the lithology of individual stones was evaluated and compared to the regional bedrock of the surrounding area.

1.2 Cirque as Evidence

1.2.1 Cirque Geometry

Cirques are very specialized landforms that form through limited erosive processes, which are almost always associated with the presence of an icemass. A cirque, as defined by Evans and Cox (1974):

"…is a hollow, open downstream but bounded upstream by the crest of a steep slope ("headwall") which is arcuate in plan around a more gently-sloping floor. It is glacial if the floor has been affected by glacial erosion while part of the headwall has developed subaerially, and a drainage divide was located sufficiently close to the top of the headwall for little or none of the ice that fashioned the cirque to have flowed in from outside."

Cirques are formed from shallow depressions on the side of a mountain. These depressions can gather snowmasses, that can endure warm spring temperatures because of favorable geographic conditions such as elevation and protection against direct sun and wind. When a snowmass persists throughout the year and accumulation exceeds ablation (melting) nivation, a term used to describe sub-snowmass processes including mass wasting and freeze-and-thaw cycles, can support the growth of a more compact icemass (Easterbrook, 1999). Over time, this residual snow gets compacted into névé and firn, and eventually turns into a dense mass of ice that can deform and flow due to its own weight. At this point the snowmass has become an alpine glacier (Figure 3).

1.2.2 Cirque Erosion

The deep cut cirques we see today are the result persistent glacial erosion. While

FIGURE 1. The Great Gulf, looking southwest. Note the mature U-shaped valley as evidence of the cirque's glacial origin (AlexeyD, SummitPost.org, 2009).

FIGURE 2. A view from the top of the headwall looking northeast into the Gulf. Again, note the mature, U-shaped valley and steep sidewalls (Tim Cook).

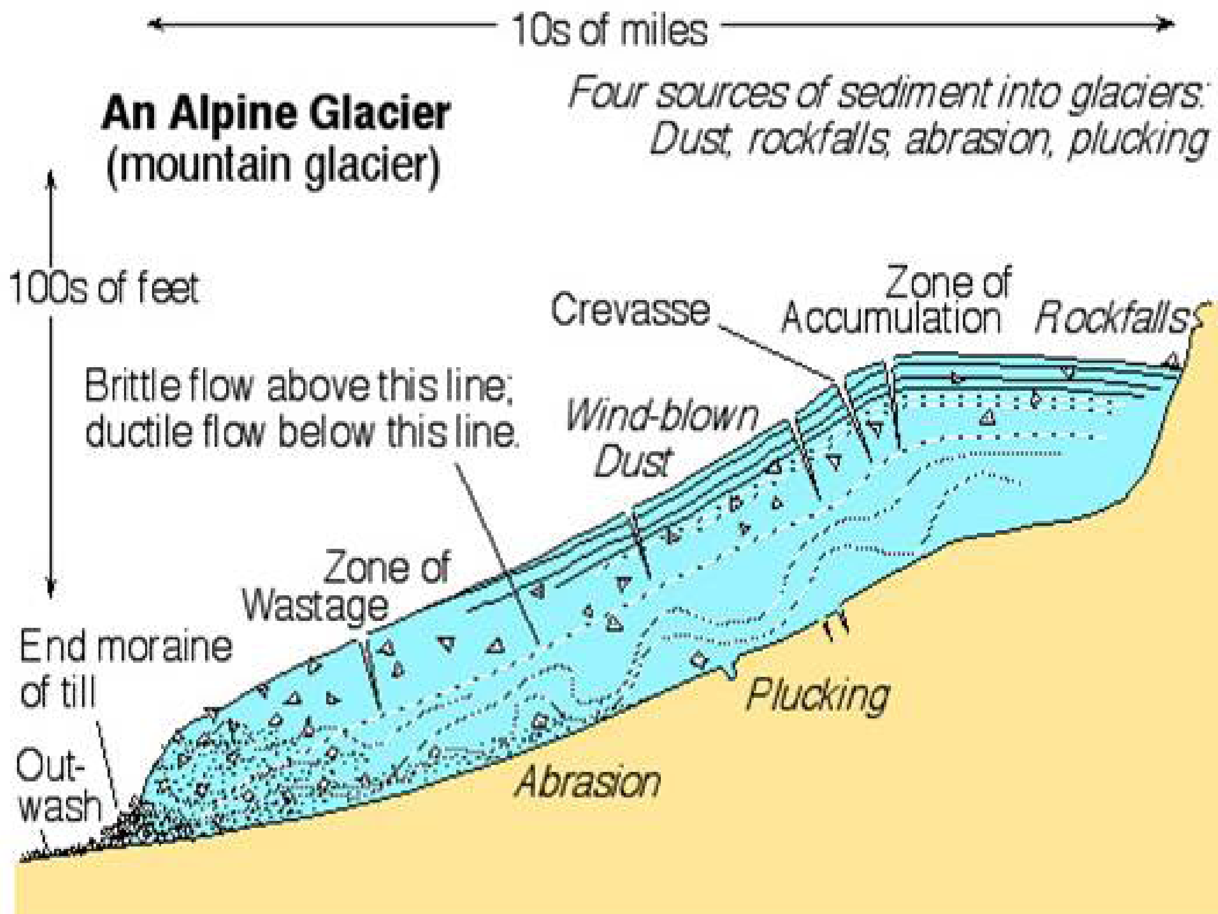

FIGURE 3. A cross-section of an alpine glacier. Note the zones of accumulation and ablation, as well as areas of rockfalls and plucking (Railsback, 2001).

the steep headwalls of cirques imply the bulk of erosive forces pluck rocks from the cliff (Riihimaki, (2005), it has been proposed that downward erosion of the cirque floor plays a larger part in the expansion of the cirque (White, 1970). Freezing and thawing of the headwall, as well as plucking, can cause headward retreat while abrasion, a result of the movement of a glacier over the cirque floor, can deepen the cirque (Figure 3). By deepening the cirque and cutting it further into a hillside these processes support glacier growth by enhancing the morphometric conditions that first permitted icemass persistence and by reducing the amount of direct sunlight that reaches the cirque floor and acting as a well for snow to get trapped. This process is known as a geomorphic feedback system, where the glacier supports its own growth (Graf, 1976).

Material that is eroded by flowing ice may be incorporated into the glacier and transported in the direction of dominant ice flow, usually towards the terminus of the ice. The size of the clasts in depositional features at the terminus can be an indicator of the method of liberation and original location in the cirque. Quarrying, which takes place on the headwall, produces coarse sediments like cobbles and boulders, whereas abrasion, which takes place on the cirque floor, produces fine sediments like silts and sands (Alley et al., 1997).

The shape of a clast can also be an indicator as to the relative location of the origin for a rock and the time it has been in transport. Generally the longer a clast has been in transport, the more rounded it is. Angular clasts with little signs of rounding have either been in transport for a short period of time or did not travel a great distance. While rounding and resistance to weathering is also dependent on clast lithology and its influence, hardness, cleavage, and susceptibility to fracture, comparing the roundness of similar lithologies can be a good indicator of the distance individual clast have travelled and the duration of travel (Boulton, 1978).

1.2.3 Glacial Deposit

As sediment is transported through a glacier it passes from the zone of accumulation to the zone of ablation, or wastage. The clasts are transported through and beneath the ice mass, some being deposited subglacially as basal till, while some is transported to the snout, or front of the glacier to form a large deposit. This deposit is known as a terminal moraine and usually marks the furthest extent of a glacier. This unconsolidated debris, or till as it is referred to, can be separated into two categories: basal till and ablation till. Basal till is material that has been deposited by the overriding glacier into the bed, or valley floor. Ablation till is material that is deposited as the ice containing it melts away (Boulton, 1978). Till deposits, especially basal till, generally have a fabric orientation. This common orientation of clasts within the till reflects the relative motion or direction of deposition from the glacier; however fabric does not always occur. Setting and morphological form can have an impact on the fabric of a till (Kruger and Marcussen, 1976). A common attribute of flow till, a type of ablation till where sediments flow off the front margin of a glacier, is an unconsolidated till with no common fabric orientation (Benn & Evans, 2010).

1.2.4 Residual Continental Drift

It should be noted that if the feature in question is a result of a reactivated cirque glacier after the recession of the continental ice sheet, there would be a thick layer of residual continental drift, erratics of northern origin, spread across the area. Before glacial erosive process took place on bedrock, it would have to remove this drift, thereby adding a population of rocks of northern origin, as well as erratic and local lithologies. Origin of drift should be taken into consideration when thinking about the erosive processes that produced the possible terminal moraine.

1.3 Climate Implications

1.3.1 Influence of Climate

It is possibly for a residual icemass in an existing cirque to reactivate and develop into a glacier. Three factors have primary influence on the mass balance, or the growth or recession) of a glacier in a pre-existing cirque: summer temperature, total winter precipitation, and solar radiation (Ohmura et al., 1992). A significant reduction in temperature combined with base-level precipitation amounts or a less significant reduction in temperature and increased winter precipitation amounts, would both permit the reactivation and readvance of an alpine glacier. The duration of growth of a glacier from these factors is dependent on the duration for which they last. If these summer temperature reductions and/or winter precipitation increases are only sustained for a short period, the growth, or readvance, of the glacier will be minor; if these changes are sustained for a long period of time, the growth will be significant. Climate data compiled by Ohmura et al. (1992), consisting of temperature and precipitation at the equilibrium line altitude of glaciers across the globe, set an approximate standard for climate conditions capable of facilitating the growth and sustenance of a glacier, and more specifically show that glaciers can form at relatively high temperatures, if a significant increase in precipitation occurs.

Changes in solar radiation can also influence glacier mass balance (Ohmura et. al, 1992; Huss et. al, 2009). Milankovitch cycles, which describe the cyclical changes in the Earth's orbit, and variations in the Sun's output, can have a significant effect on a glacier, but tend to have changes of significant magnitude on a much longer timescale than that which is associated with short-lived alpine glaciers. However, if we examine data from Berger and Loutre (1991), it is worth noting that post-glacial average summer

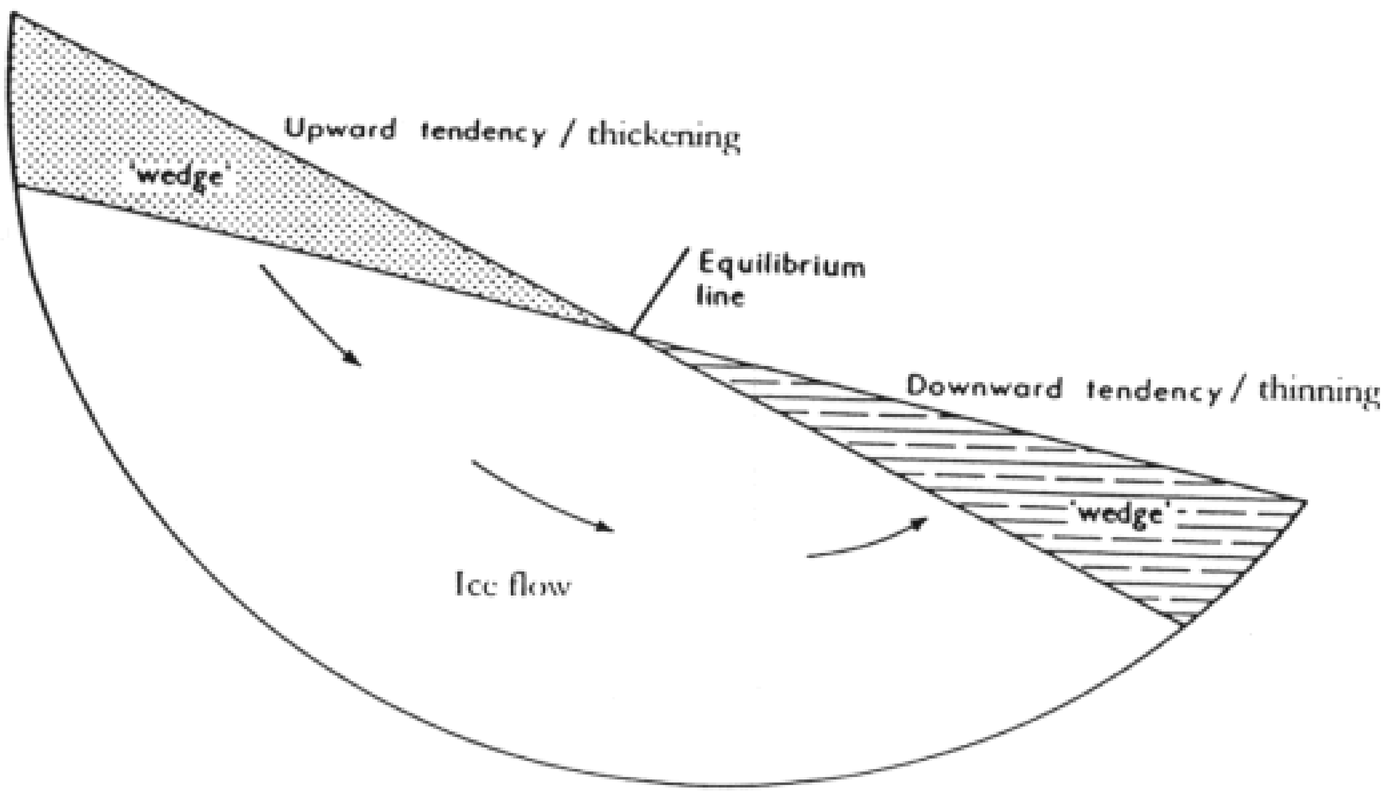

FIGURE 4. An idealized glacier showing variations in accumulation and ablation, separated by the equilibrium line, as well as basic ice flow direction (Sugden & John, 1976).

insolation was highest 12,000 to 11,000 years BP during the last 30 thousand years; 40 W/M^2 higher than contemporary values, while average winter insolation was 16 W/m^2 less than contemporary values. The amount of radiation a glacier receives can also be affected by the aspect of a cirque. In the Northern Hemisphere, a northerly-facing cirque will not receive as much direct sunlight, and therefore solar radiation, as a southerly-facing cirque, making it more suitable for the development of an alpine glacier (Evans, 2006).

1.3.2 Determining Paleoclimate

Because certain climate conditions are necessary to promote the growth of an alpine glacier, the altitude, orientation, and morphometry of the corresponding cirque can tell us much about the paleoclimate conditions well after the glacier has disappeared (Davis, 1999). On active glaciers the relative mass balance, or ratio of the accumulation zone to the ablation zone, can be determined using the equilibrium-line altitude (ELA) (Figure 4). The equilibrium line is the boundary of the accumulation and ablation zones on a glacier, an elevation that neither gains nor loses ice mass. The climate at the equilibrium line is considered to be minimally sufficient to maintain glaciers (Ohmura et al., 1992). By monitoring the conditions at this line, as well as changes in the altitude of this line, a better understanding of a glacier's response to climate change can be obtained. However, without a glacier the ELA can be difficult to determine. Flint (1971) proposed that the altitude of the cirque floor was the approximate snow-line at the time of cirque erosion via an alpine glacier. However, Meierding (1982) compared several methods of estimating ELAs and found that the cirque floor altitude provided an underestimate. Using the schrund altitude of a cirque offers a more conservative estimate of former ELAs. The schrund altitude is the most obvious break in slope between cirque headwalls and floors as seen by a change in spacing between contour lines (Davis, 1999). This break represents the former location of the bergschrund, a crevasse that separates the moving ice mass from the stagnant ice above (Benn & Evans, 2010). Goldthwait (1970) proposed that schrund elevations were dependent on cirque orientation, implying that solar radiation played an important part in mass balance in addition to summer temperature and winter precipitation. Although not as accurate as primary methods, the Toe-Headwall-Altitude-Ratio (THAR) method, which compares the altitude of the toe of a glacier to that of the headwall, provides an estimate of a former glacier's ELA using valley morphology. Likewise a reconstruction of the former icemass would also allow for an Area-Accumulation Ratio (AAR) if the surface area of the glacier can be calculated (Leonard, 2003)

The overall size of a cirque can also give insight into the paleoclimate conditions at the cirque. Cirque elevation profiles can provide useful information about erosion on the headwall and cirque floor, and cirque volumes can reveal details about previous glaciations and respective durations. Evans and Cox (1995) developed a classification for cirques, assigning grades (1-5) based on their previous definition (Evans & Cox, 1974). Cirques displaying textbook attributes are assigned a grade of 1, whereas cirques with marginal characteristics and doubtful origins are assigned a grade of 5.

1.4 Study Area

1.4.1 Regional Deglaciation

The study area is the Great Gulf cirque complex located in the Presidential Range of the White Mountains in Coos County, New Hampshire (Figure 5, 6, 7), an area with a complicated glacial history. Based on evidence from the Bethlehem Moraine complex, a morainic belt composed of hummocks and ridges of glacial sediments northwest of the

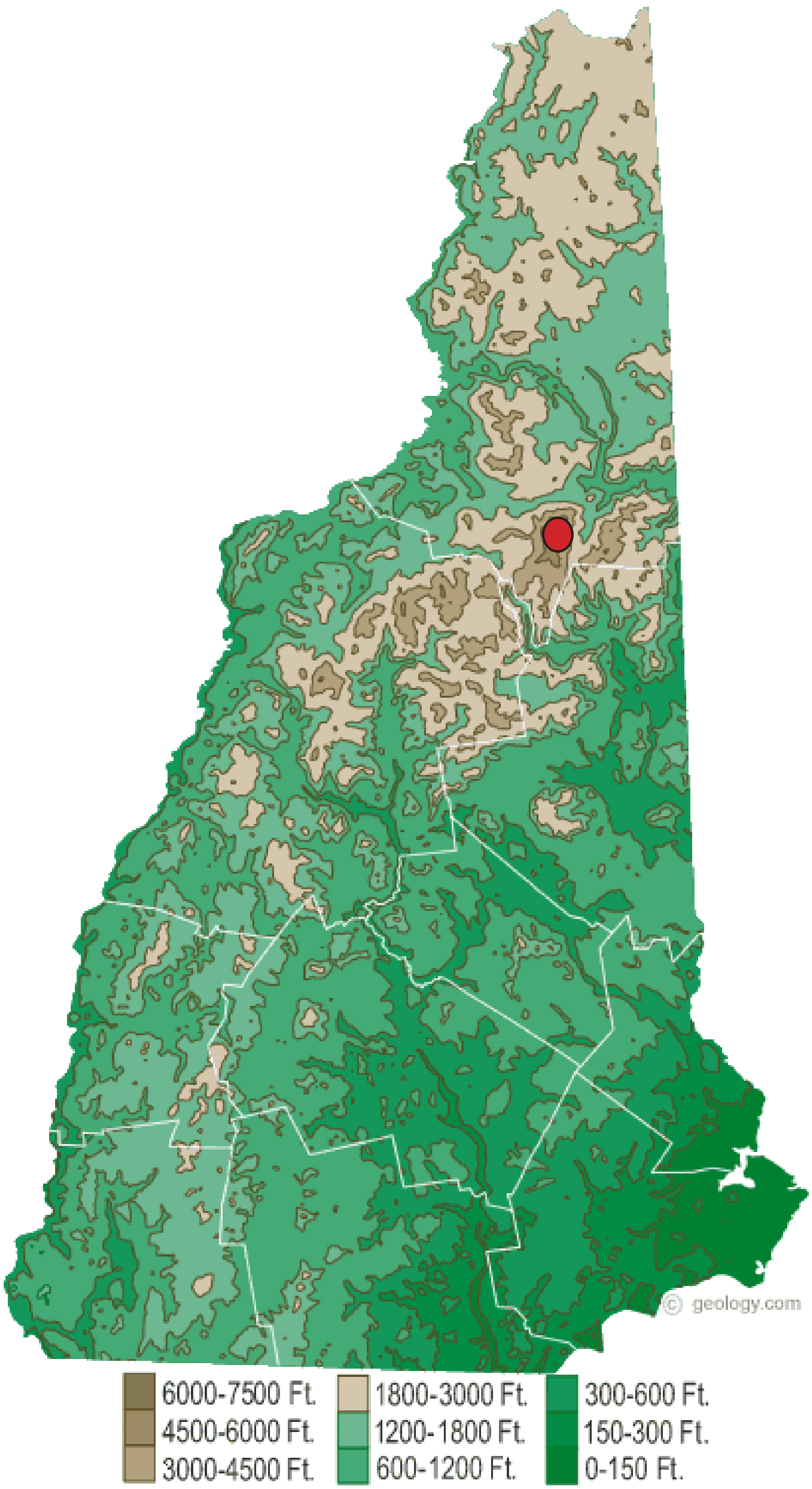

FIGURE 5. A topographic map of New Hampshire with study area indicated with red dot (Geology.com, 2012).

FIGURE 6. The Presidential Range with the Great Gulf indicated (GoogleEarth, 2012).

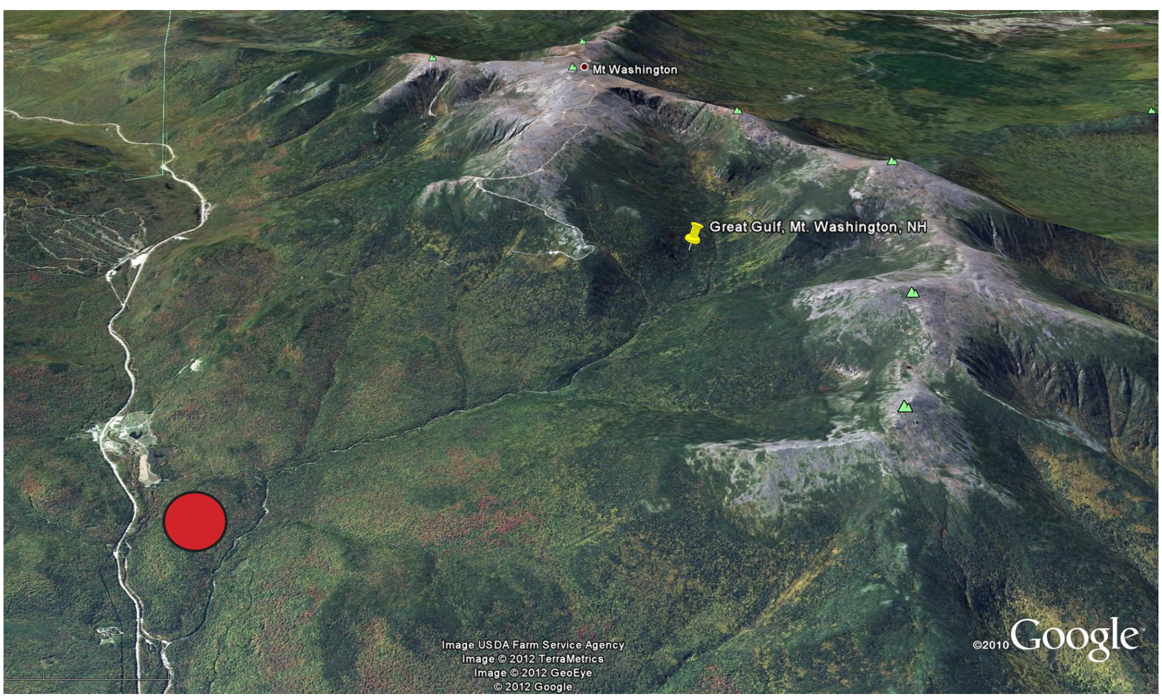

FIGURE 7. The Great Gulf, as viewed from the northeast, with location of proposed terminal moraine indicated with red dot (GoogleEarth, 2012).

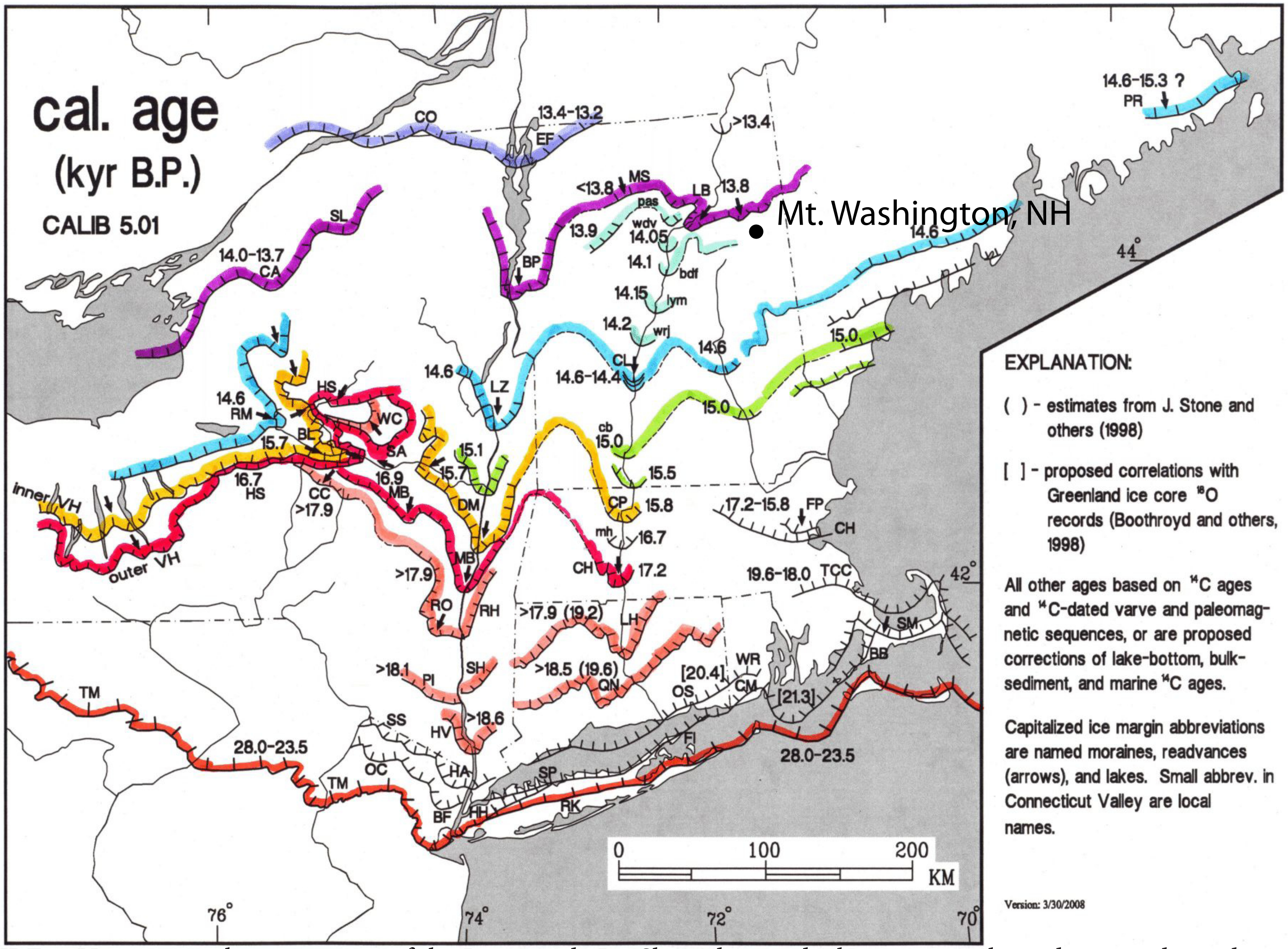

FIGURE 8. Various southern margins of the Laurentide Ice Sheet during deglaciation, with srudy site indicated. Adapted from Ridge (2008).

Great Gulf, as well as radiocarbon ages obtained from around the region, the recession of the Late Wisconsin ice margin from the White Mountains occurred between 12,500 ± 350 and 11,400 ± 50 cal ^{14}C years BP (Figure8) (Thompson et al., 1999). Sequences of glaciolucustrine deposits and meltwater drainage channels indicate a northward recession of an active ice margin, as opposed to a model of stagnation and downwastage that was popular during the mid-1900s. In addition, Thompson et al., (1999) propose that the Bethlehem Moraine complex was formed by a readvance and oscillatory retreat of the Connecticut Valley lobe of the Laurentide Ice Sheet, called the Littleton-Bethlehem Readvance, and attribute it to the Older Dryas climate reversal. The Older Dryas was a stadial period between 12,100 ± 90 and 11,900 ± 70 cal ^{14}C years BP. As global temperatures rose after the LGM causing the ice sheet to recede there were several climate reversal that caused rapid cooling across large parts of the globe. The significance of evidence for a reactivation of a cirque glacier near the study area is very important in determining the magnitude of such a cooling event in the area, as we can determine what conditions the climate would have had to attain to create or reactivate a glacier.

1.4.2 Paleoclimate

After the recession of the continental ice sheet the climate of New England underwent several periods of abrupt climate reversal. These stadials, periods of colder temperatures during a general time of warming, only lasted up to a few hundreds of years, but caused significant drops in temperatures around the region. These changes in temperature are recorded in many natural systems, most importantly in lake sediments. Characteristics of lake sediments such as varve thickness, percent organic matter, and plant and pollen macrofossils can tell us the magnitude and timing of such changes, and correlated with other proxies to develop strong hypotheses about the paleoclimate of an area (Cwynar and Spear, 2001; Shuman et al., 2005).

A previous study (Thompson et al., 1999) reexamined the Bethlehem Moraine complex, located less than 15 km to the northwest of the Great Gulf, and determined through correlation to deposits in adjacent areas as well as Connecticut Valley varve chronology (Ridge et al., 1999) and radiocarbon ages (Thompson et al., 1996) that a readvance of a lobe of the Laurentide Ice Sheet could be associated with the Older Dryas climate reversal. The proximity of such a readvance to the study area suggests that the climate reversal could have been significant enough to reactivate an ice mass within the cirque.

Additionally, several lakes in the White Mountains have been cored and the results have been correlated with similar studies around the region to develop a chronology of late-glacial climate of the White Mountains (Cwynar and Spear, 2001). Percent organic matter and chironomid assemblages found in three lake sediment cores present convincing evidence of late-glacial climate events in the White Mountains. The most significant event is marked by a section of core with a low percentage of organic matter indicating colder temperatures. Calendar ages bracket this event between 11,250 ± 70 years BP and 10,635 ± 35 cal ^{14}C years BP, which is consistent with a GS-1 (Younger Dryas) age for this event.

When quantified, the magnitude of this event in the White Mountains was found to be less significant than it was in Maritime Provinces and adjacent Maine (Levesque et al., 1993). While those areas experienced a temperature decline of 12-20°C, the White Mountains experienced lake water temperature drops of around 5°C (Cwynar & Spear, 2001) at mid-elevation lakes around 700m, which suggests some attenuation of the Younger Dryas event from the Maritime region westward.

TABLE 1. The geometric characteristics of the Great Gulf and associated cirques, adapted from Davis (1999).

Cirque Name	Cirque Grade (°)	Schrund Altitude (m)	Aver. Height (m)	Aver. Width (m)	Cirque Length (m)	Aver. Headwall Slope (°)	Aver. Floor Inclination (°)	Cirque Volume (km^3)
Upper Great Gulf	10 (~N)	1350	650	1065	2135	42	9	0.74
Jefferson Ravine	105 (~E)	1260	570	990	1675	38	11	0.47
Sphinx Basin	100 (~E)	1470	270	535	610	31	21	0.04

1.4.3 Modern Climate

The average summer temperature in the Great Gulf is about 14.4° C according to summit data compiled from 1971 to 2000 (MWO, 2011) and a lapse rate of 6.2° C/km (Cwynar & Spear, 2001). Using estimates from Ohmura et al. (1992), we would expect mean summer temperatures of around 1° C assuming some precipitation in order to permit the growth of a glacier, although increases in precipitation can allow for favorable conditions with warmer temperatures. Under the Koppen climate classification system, the White Mountains fall under a subarctic climate characterized by long, usually cold winters, and short, cool to mild summers. Mount Washington is an exception to this pattern in that subarctic climates occurring at high altitudes in otherwise temperate regions have extremely high precipitation due to orographic lift. Mt. Washington receives an average rain-equivalent of 2600 mm of precipitation per year (MWO, 2011). It is worth noting that these data are from the summit. Tuckerman's Ravine, an adjacent cirque on the southeast side of Mt. Washington, can frequently receive more than 30 m of snow accumulation on the cirque floor per year from wind-driven snow (Haven, 1960). Because of its size and depth, the Great Gulf is a significant basin in which snow could accumulate over a single season, especially if annual precipitation were greater.

1.4.4 White Mountain Cirques

Cirques are found throughout New England on virtually every significant mountain range. Well-developed cirques can be found near Mount Katahdin (ME), the Longfellow Mountains (ME), the Adirondack Mountains (NY), the Catskill Mountains (NY), the Green Mountains (VT), and the White Mountains in New Hampshire (Davis, 1999). However, the most well developed, as defined by Evans & Cox (1995), are found in the most prominent mountains, Katahdin and the Presidential Range in White Mountains.

The Presidential Range contains 17 distinct cirques that vary greatly in size, shape, and orientation (Davis, 1999). The largest, most voluminous, and most well-developed is the Great Gulf cirque complex. The Great Gulf cirque complex (Figure 6, 7, 9; Table 1) is composed of three cirques: the main cirque, the Great Gulf; and two tributary cirques, Sphinx Basin and Jefferson Ravine. The Great Gulf is located on the north side of Mt. Washington, below Mt. Clay. The two tributary, or "feeder," cirques are located directly north of the Great Gulf between Mt. Clay and Mt. Jefferson, and Jefferson's Knee ,a faceted spur created by converging ice flows across its slopes from the Great Gulf, Sphinx Basin, and Jefferson Ravine [Fowler, pers. Com., 2011], and Mt. Adams. Listed below are the morphometric characteristics of the three cirques:

1.4.5 Research History

Agassiz (1870) was the first to recognize that the cirques in the region were carved by alpine glaciers and not continental ice, or any other erosional methods capable of scouring a ravine of that magnitude. Goldthwait (1913) stated that because of their maturity, the development of the cirques must have preceded the last advance of the continental ice sheet, a view supported by Antevs (1932), but that the cirques may have

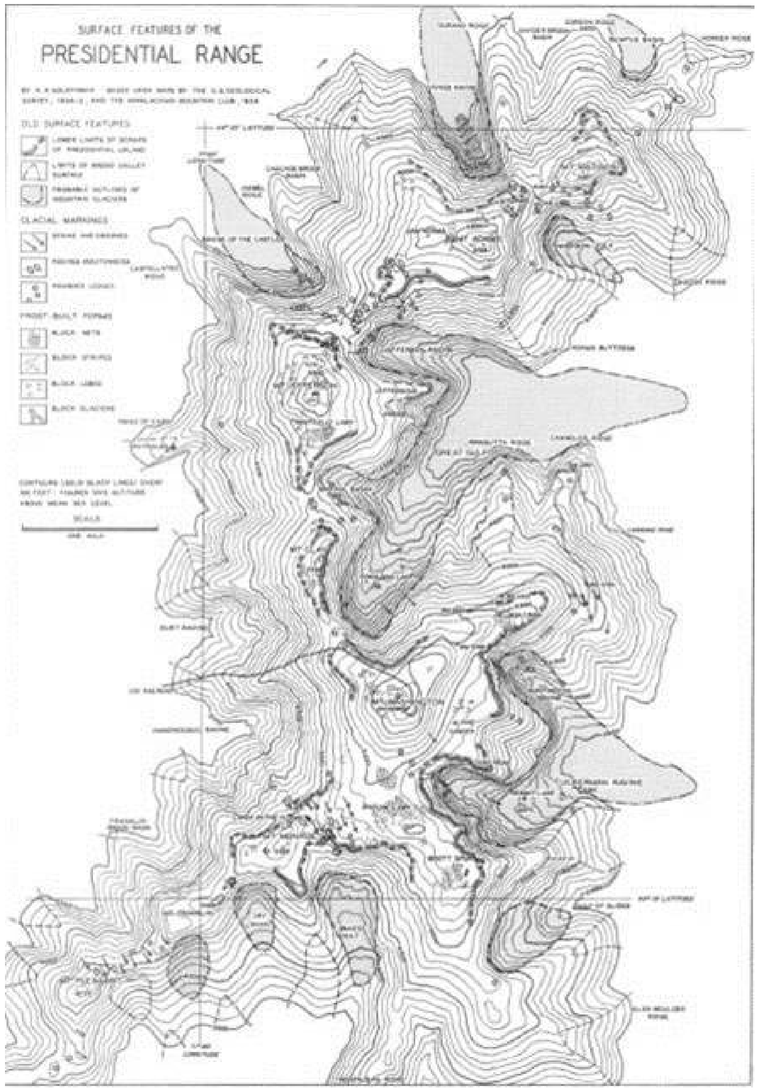

FIGURE 9. The Presidential Range with reconstructions of former ice masses within cirques (Goldthwait, 1970).

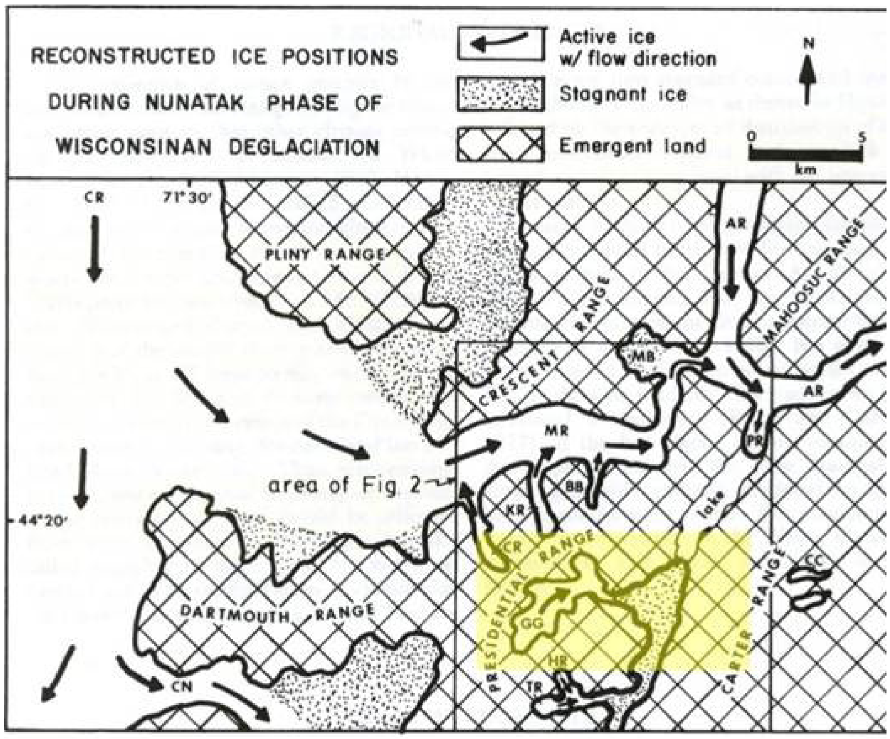

FIGURE 10. Proposed theory of nunatak-stage reactivation of ice masses, with the Great Gulf highlighted, adapted from Bradley, 1981.

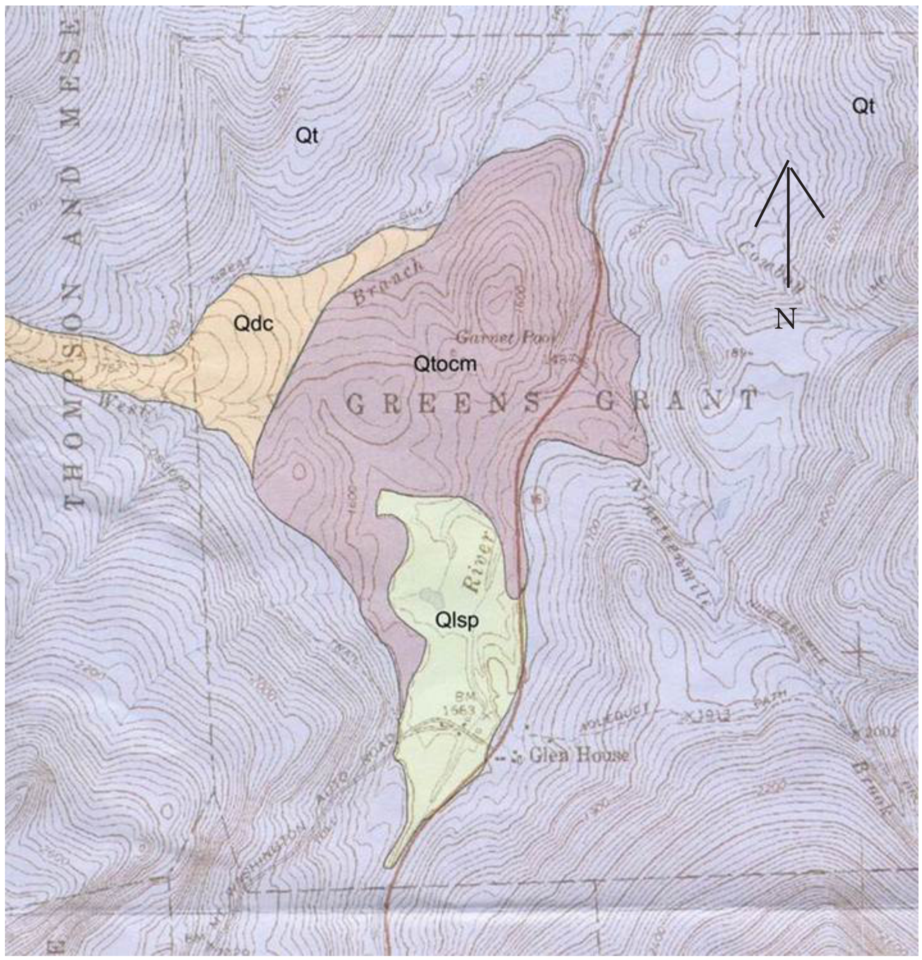

FIGURE 11. A terminal moraine (Qtocm) associated with a reactivation of a local glacier in the Great Gulf, Proposed by Fowler (2011). Note residual continental drift (Qt) associated with the Laurentide Ice Sheet, as well as Qlsp, glacial lake sediments associated with a proposed lake damned by the terminal moraine.

been occupied after the ice sheet retreated, noting "extensive piles of angular blocks of local rocks on the floors of the ravines." He noted that if these piles were indeed terminal moraines, the alpine glaciers that deposited them were relatively small compared to those that carved out the cirques. He concludes by stating that if the piles are not moraines, ten no local glaciers were active after the ice sheet.

Antevs (1932) and Johnson (1933) also support the idea that the cirques were carved before the last ice sheet covered the White Mountains, with Antevs noting that any of the former glacial epochs of the Pleistocene could have formed the cirques. Antevs noted that if local alpine glaciations did exist after the retreat of the Wisconsinan ice sheet, morainic evidence would be present at the mouths of the cirques. He concluded that the absence of such features suggests their eradication by the continental ice sheet, and that the latest period of erosion that took place in the cirques was due to the overriding ice sheet. Johnson (1933) argued that such reasoning is not sound, citing examples in Europe where alpine glaciers rarely produce significant terminal moraines. He believed that continental ice was not capable of forming the cirques and that despite the lack of evidence of moraines, local alpine glaciers most likely existed after the recession of the ice sheet.

Goldthwait (1970) was the first to perform a detailed study of alpine glaciations in the Presidential Range. Like his predecessors, he recognized the formation of the cirques from alpine glaciers, but found evidence, mainly northern drift in the ravine floors and the absence of terminal moraines, convincing enough to state that continental glaciations came after all significant local alpine glaciations in the area. However, it is important to note that no drift of northern origin was found in the Great Gulf. Goldthwait (1970) stated that a residual ice mass could have persisted in the Great Gulf following continental deglaciation. Still, Goldthwait (1970) provided the basis for much of the morphological data used for later studies (Davis, 1999) and used these data to reconstruct former glacier locations, as well as the conditions necessary to permit alpine glacier growth in the cirques (Figure 9). He believed that in order to support an ELA between 900 to 1,200 m in altitude, the summer climate relative to today's climate would need to have been at least 9.3° C cooler. However, if annual precipitation "increased markedly", a temperature reduction of only 5.5° C is needed (Goldthwait, 1970).

Bradley (1981) proposed a hybrid idea, stating that alpine glaciations in the cirques may have occurred during the nunatuk phase of continental ice retreat, when continental ice still occupied the lower valleys, but the peaks of the White Mountains were exposed. He proposed that alpine glaciers formed in favorable cirque locations (such as northerly aspect, or deep-cut cirques) and were tributary to streams of the continental ice sheet that ran through the valleys. Specifically he cited King Ravine on the northern end of the Presidential Range as a location for post-Wisconsinan reactivation of an alpine glacier based on drift of a southern origin (up-cirque) lower in the valley, providing evidence against alluvial origin (Figure 10), and identified a feature he believed to be a terminal moraine deposited during from an active ice mass in the ravine. He also proposed that the Great Gulf was a favorable cirque for reactivation of alpine glaciations and that the lack of a terminal moraine could be attributed to a stagnant ice mass in the valley below, isolated from the continental ice sheet by a glacial lake dammed in the Peabody River Valley (Figure 6). However, the integrity of his stone counts were called into question, most notably by (Gerath and Fowler, 1982) who found no convincing evidence of post-Wisconsin alpine glaciations in Bradley's argument. Fowler (1984) and (Waitt and Davis, 1988) subsequently proposed the deposit was colluvial in origin.

1.4.6 Current Research

Recently it has been proposed by Fowler (2011) that a depositional feature on the valley floor at the mouth of the Great Gulf cirque complex is a terminal moraine associated with the Older Dryas stadial period (Figure 7, 11). The significance of such a feature could not be understated, as the absence of a terminal moraine has long been the evidence against a reactivation of an alpine glacier in the region during post-Wisconsinan time. The feature is described as a "hummocky, heavily dissected morainal complex" composed of a clast and matrix-supported flow till with abundant boulders(Fowler, 2011). However, the origin of the feature cannot be clearly stated until the provenance of the till can be determined. If the till contains clasts that originate from within the cirque complex, it can be concluded that the moraine was formed after the recession of the continental ice sheet from the valley and it is the product of an alpine glacier. However, if the till contains clasts that originate from the north, the moraine could be a result of a readvance of the continental ice sheet, which could still be associated with the Older Dryas readvance. In order to establish the provenance of the moraine stone counts, the same method used by previous researchers in the region (Goldthwait, 1970; Bradley, 1981; Fowler, 1984), would be used to determine the lithologies of the clasts within the till and then compared to the local lithologies, noting the location.

Methods

2.1 Initial Field Work

In order to determine the origins of the proposed terminal moraine at the mouth of the Great Gulf, representative samples of the till composing the moraine were taken by digging five test pits across the landform, sampling ~50 hand-sized stones from each pit, and determining the provenance of the stones. The method is similar to that of previous studies of determining the origins of a possible glacial landform (Fowler, 1984; Goldthwait, 1970; Bradley, 1981; Waitt and Davis, 1988).

The selection of test pit locations was chosen in order to sample a wide area of the landform, but was partially limited by proximity to the pre-existing trail network in the region. The locations of the test pits on the feature are important as there could be variations of till characteristics depending on the proximity to the snout of an associated glacier. If samples are collected from different locations, a better understanding of these variations can be obtained. The other location parameter was the proximity to the pre-existing trail network. Because the landform lies within a Wilderness area, test pit locations were limited to within a ~30 foot corridor from the center of the trails. Locations that were off the main trail but free of trees and brush were selected in order to avoid digging through the layer of gravel directly underneath the trails. Two of the pit locations are located on the cirque-side of the landform (Wilding and Drifter), two are located on the valley side closer to the northern end of the feature (Thumper 1 and 2), and the fifth is located on the extreme southern edge of the feature (Libby) (Figure 12).

When a location was selected, a backhoe provided by the Mt. Washington Auto Road was used to first remove a layer of topsoil and then dig a 2-meter-long trench approximately the width of the bucket, which was about 1 meter across (Figure 13). The removed till was placed in a pile adjacent to the pit, but separate from the topsoil, so as not to contaminate the sample with surface stones. Hand-sized stones were chosen over larger

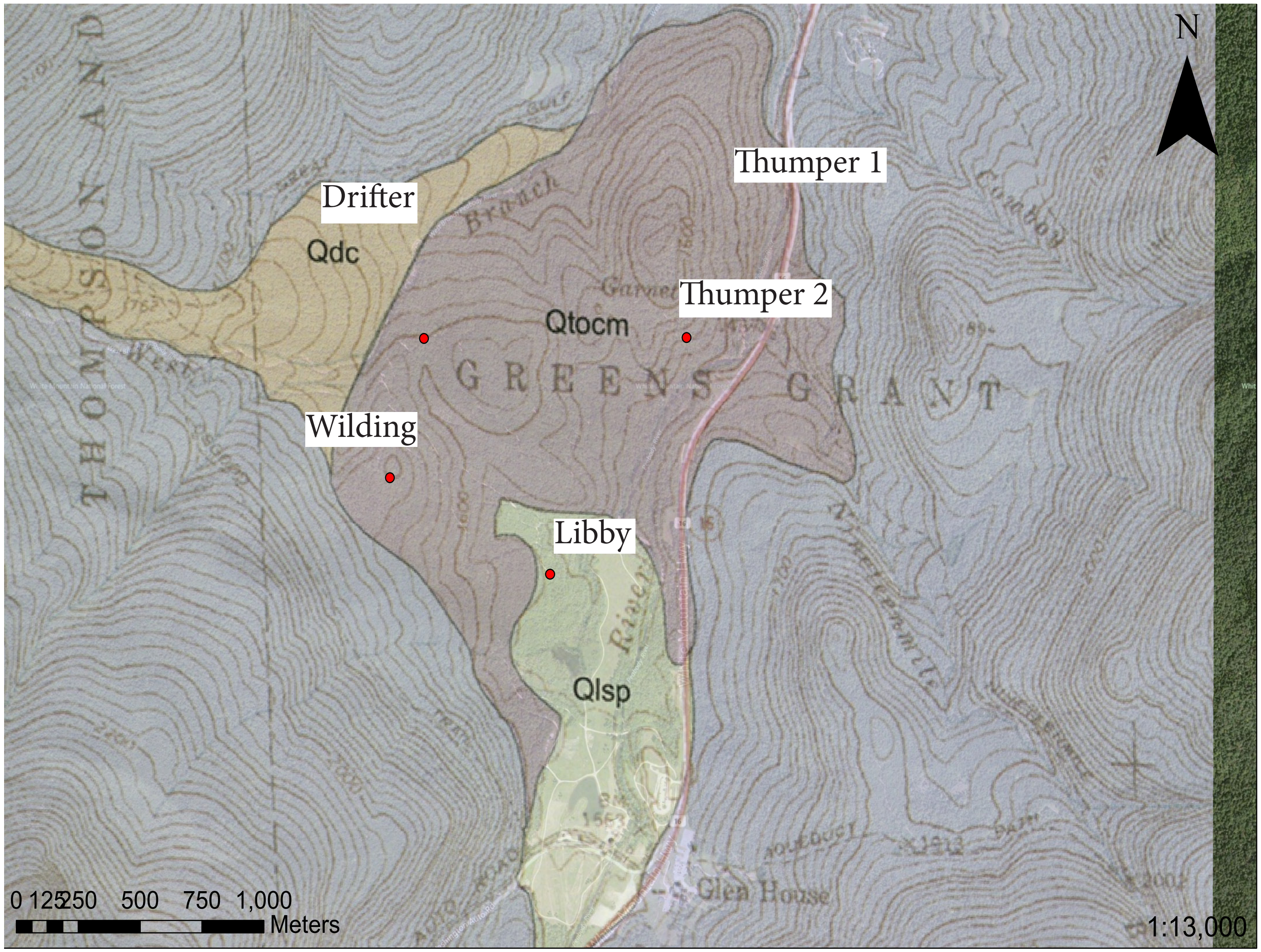

FIGURE 12. The locations of test pits (red dots) relative to the feature as mapped by Fowler (2011).

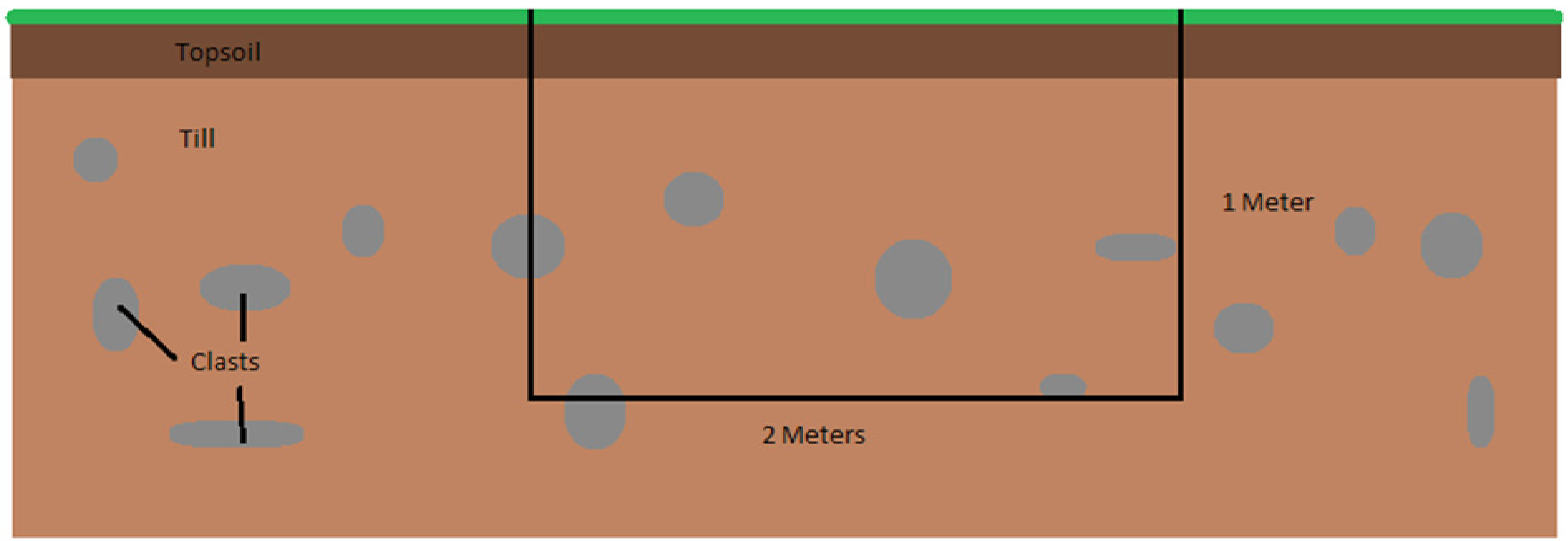

FIGURE 13. A cross-section schematic of a test pit.

or smaller stones for consistency, both between pits in this study, and with other studies (Fowler, 1984; Goldthwait, 1970; Bradley, 1981; Waitt and Davis, 1988), as well to reduce the impacts inherit when dealing with ≈250 stones. If 50 stones could not be recovered from within the pit, stones were chosen at random from the excavated till, making sure not to take surface stones from below the pile. Once 50 stones were selected, they were put into a sample bag and taken to Bates College in Lewiston, Maine, for identification.

2.2 Stone Classification

In order to identify the stones and associate them with a known local lithology, they were first rinsed with water to remove excess dirt and provide a clean surface to write on identification information. The stones were then numbered and relative size and shape measurements were taken. The long and intermediate axes of the stones were measured in centimeters. These numbers were later multiplied to give the stones a "size" class. While this number does not represent the area or volume of the stone, it does provide a parameter by which all the stones can be compared. The size of a clast can help determine the relative age of the clast, as larger stones are usually younger, or more local, whereas smaller stones have been in the erosional system longer (Alley et al., 1997). Basic roundness measurements were also taken using a 1 to 4 scale, where 1 means a stone is round and 4 means a stone is angular. Using the scale established by Krumbein (1941b), the more angular stones were about 0.2 P while the more rounded stones were about 0.6 P. The roundness of a clast indicates the relative age of the clast. Younger, more local clasts will still retain sharp angles from fracturing, whereas older clasts that have been in the system tend to be rounder and smoother. Clast shape can also be related to the mechanism of transport; whether a rock is englacial, which would include more angular rocks from the headwall and sidewalls of the cirque, or supraglacial, which would include more rounded rocks plucked from the cirque floor.

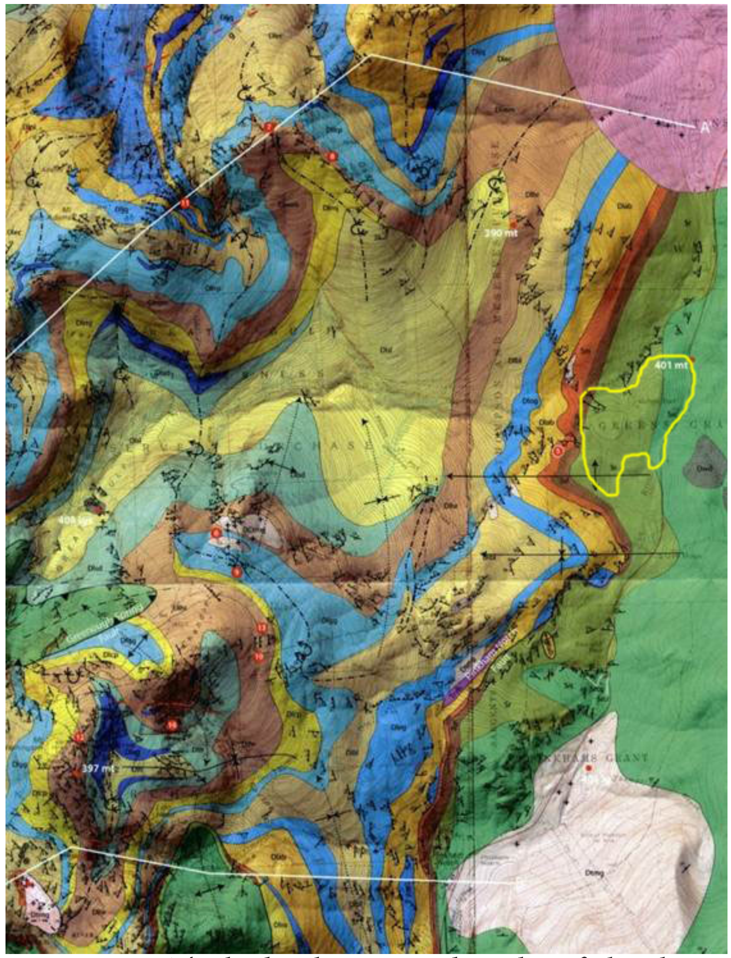

FIGURE 14. The bedrock map used to identify local lithologies within the proposed terminal moraine outlines in yellow, adapted form Eusden (2010).

Once the rocks were measured and indexed, a fresh surface was exposed by cutting the stones with Diamond Pacific TR Series slab saw. Because of the intense weathering present on some samples, a fresh surface was exposed to get a consistent surface from which to identify the stones. Once cut, the stones were again separated by pit and sorted.

The stones were sorted on basic visual characteristics like cleavage patterns and color, and then further sorted by more specific characteristics such as foliation, grain size, and mineralogy, specifically the presence of biotite and potassium feldspar in granites. When the stones could no longer be sorted by visual characteristics, they were identified, if possible, as a local lithology using the most current bedrock map of the area (Figure 14) (Eusden, 2010). The lithology of the stones was used to trace them to a specific locality according to the bedrock map. Using the textural data gathered earlier, a relative age association was also assigned to each stone.

For the study, certain local lithologies were attributed to cirque, northern, or adjacent origins in order to determine where the majority of material in the landform was derived from. DCtmg, a binary granite found directly up-valley from the landform was used as the northern indicator. The Rangeley formation (both Sr and Src) was used as the adjacent indicator, as this type of rock could have been deposited from processes both within the cirque and from the north. However, the Rangeley Formation is also on the headwall and sidewalls of the cirque, so it is possible that a large percentage of the population could be derived from the cirque. The specific lithologies associated with the cirque are the Little Formation (Dl), the Madrid Formation (Sm), the Smalls Falls Formation (Ssf), a granite-diorite (Dwd), and various pegmatites, of which there are several types found in the Great Gulf. Any rocks not identifiable or not found to be one of these lithologies were classified as erratic.

2.3 Ice Mass Reconstructions

The profile of a paleoglacier that may have occupied that Great Gulf was constructed using the known physical parameters of the cirque today. The geometry of the reconstructed ice mass was then used to evaluate the climatic conditions needed to support a local glacier within the Great Gulf.

ArcGIS was used to gather data on the geometry of the cirque. A digital elevation model (Gesch et al., 2011) was used to create elevation profiles of transects running down the cirque and across the cirque. These ground profiles were then used to model the former ice surface using the basal shear stress equation:

$$\tau_b = \rho g h(\sin\alpha)$$

where τ_b is basal shear stress, ρ is ice density, g is gravity, h is the height of the ice mass, and α is the slope of the ice mass surface (Patterson, 1994). Ackerly (1989) used this equation to reconstruct former ice masses in the White Mountains. This study was the first to use a digital elevation models to obtain geometrical data on the cirque, as well as the first to use a landform to constrain the terminus of a reconstructed glacier in the area.

Benn and Hulton (2010 a,b) provided an Excel spreadsheet program to reconstruct the ice surface profile of former mountain glaciers and ice caps using the above equation as well as ground surface profiles generated in ArcGIS. A vertical ground profile of the valley is used as well as a shape factor derived from the cross section of the valley. Because no target elevations are available a range of shear stress values were used ranging from 0.5 bars to 0.9 bars, values for cirque glaciers found in various studies (Sanders et al., 2010; Weertman, 1971; Benn pers comm., 2012). An ice thickness was then calculated. Using cross-sectional data and ArcGIS, we then used this ice thickness to draw the surface outline of the glacier on a map.

2.4 Paleoclimate Reconstructions

Using the morphometric data from the valley and the surface outline of the glacier within the valley we can then use the THAR and AAR methods for estimating the ELA of the former glacier (Leonard, 2003). To generate an ELA using the THAR method, the difference in elevation between the headwall and the toe is multiplied by the THAR factor (between 0.35 and 0.4). This number is then added to the elevation of the toe to get an ELA. The AAR method uses the elevation of the line separating the glacier into some ratio of accumulation to ablation areas. A glacier in steady-state is said to be ≈60% accumulation by surface area (Benn et al., 2005), so in this study, I applied that value. After an ELA was obtained, the modern climatic conditions, such as average summer temperature and annual precipitation, at the ELA were compared to those at the ELAs of dozens of glaciers from around the world to determine the disparity between the modern climate in the Great Gulf and that capable of supporting the growth of a glacier using a global data set (Ohmura et al., 1992)

Results

3.1 Stone Counts

The Libby pit (Figure 12; Table 2) was characterized by a high percentage of binary granite variations, foliated and non-foliated, that contain varying amounts of potassium feldspar. 62% of the stones were identified as DCtmg, a binary granite, while 16% was single mica granite, 8% was some other granitoid, 6% was basalt, 6% was an unidentifiable dark, foliated rock, and 2% was Rangeley Formation. The stones found in the Libby pit were the smallest and the roundest of the five pits. No common clast orientation was found.

The Wilding pit (Figure 12; Table 3) was characterized by a diverse group of lithologies. DCtmg made up 17% of the stones, as did unidentifiable granitoids, while single mica granite composed 15% of the stones, the Littleton Formation composed 13%, unidentified mafics were 10%, Rangeley Formation, both migmatized and unmigmatized, made up 10%, basalt made up 6%, with the rest being minor types. The stones found in the Wilding pit were the third largest and the most angular of the five pits. No common clast orientation was found.

The Drifter pit (Figure 12; Table 4) was characterized by a high percentage of the Littleton formation, a dark, foliated schist. The Little Formation made up 36% of the stones, while an unidentified fine-grain schist made up 12%, single mica granite made up 10%, other granitoids made up 8%, and the rest was composed of the Smalls Falls Formation, Rangeley Formation, DCtmg, and other minor lithologies. The stones found in the Drifter pit were second largest and the fourth most angular of the five pits. No common clast orientation was found.

The Thumper 1 pit (Figure 12; Table 5) was characterized by a large percentage of Rangeley Formation, both migmatized and unmigmatized. The Rangeley Formation made up 56% of the stones, while unidentified granitoids made up 16%, and DCtmg made up 12%. The stones found in the Thumper 1 pit were the largest and the third most angular of the five pits. No common clast orientation was found.

The Thumper 2 pit (Figure 12; Table 6) was characterized by a complete lack of DCtmg, but instead contained a large percentage of unknown granitoids (28%), as well as a large percentage of pegmatite (13%) and Littleton Formation (9%). The majority of the rest of the constituent lithologies were erratic of unknown origin, and a small percentage of Rangely Formation (8%). The stones found in the Thumper 2 pit were the fourth largest and the second most angular of the five pits. No common clast orientation was found.

TABLE 2. The stone count from the Libby pit.

#	Long	Intermedia	"Size"	Roundess	Lithology	#	Long	Intermedia	"Size"	Roundess	Lithology
1	11.5	6	69	2	Basalt	26	7	4	28	2	DCtmg-F
2	13	5.5	71.5	1	DCtmg-k	27	6	5	30	3	Single Granite
3	8.5	7	59.5	1	Basalt	28	6.5	5.5	35.75	2	Basalt
4	9	6	54	2	DCtmg	29	6	4.5	27	2	DCtmg-k+
5	9.5	5.5	52.25	1	DCtmg-k	30	6	5	30	2	DCtmg-F
6	9	6	54	1	DCtmg-k	31	6	6	36	2	DCtmg-k
7	9.5	7	66.5	1	DCtmg	32	6	4	24	2	DCtmg-k
8	10	6.5	65	2	DCtmg	33	6.5	4.5	29.25	3	Single Granite
9	9	8	72	1	DCtmg	34	6	4	24	3	DCtmg
10	9	6.5	58.5	2	DCtmg-F	35	6	5	30	2	Other Dark Foliated
11	8	7	56	2	DCtmg-k+	36	6.5	4	26	2	Other Dark Foliated
12	7	5.5	38.5	1	Other Granitoid	37	6	4	24	2	Single Granite
13	8	6	48	1	DCtmg	38	6	3	18	2	DCtmg-k+
14	8	6	48	1	Single Granite	39	5.5	4	22	2	Single Granite
15	9	6	54	2	Other Dark Foliated	40	5	4.5	22.5	3	DCtmg-F
16	7.5	4.5	33.75	1	DCtmg	41	5.5	3.5	19.25	2	DCtmg-k+
17	6	6	36	2	DCtmg-k+	42	6	5	30	2	DCtmg
18	7.5	5.5	41.25	1	Other Granitoid	43	6	5	30	1	DCtmg-k+
19	7.5	5	37.5	2	DCtmg-k+	44	5	4	20	2	DCtmg-k+
20	7.5	5	37.5	2	Pegmatite	45	5.5	5	27.5	2	Other Granitoid
21	8.5	5.5	46.75	2	Quartz	46	6	3.5	21	3	Single Granite
22	7	5	35	2	DCtmg-F	47	6	4	24	3	Sr
23	6.5	4	26	3	Single Granite	48	6	4	24	3	DCtmg-k+
24	6	4	24	2	Single Granite	49	4	3	12	1	DCtmg-k+
25	7.5	4	30	2	DCtmg-k+	50	5	4.5	22.5	3	Other Granitoid

TABLE 3. The stone count from the Wilding pit.

#	Long	Intermedia	"Size"	Roundess	Lithology	#	Long	Intermedia	"Size"	Roundess	Lithology
1	18.5	13	240.5	3	Sr	27	8	6.5	52	3	Other Granitoid
2	20	15	300	3	Single Granite	28	9	6	54	4	Pegmatite
3	14	9	126	3	Sr	29	7.5	7	52.5	3	Other Granitoid
4	15	10	150	2	Dl	30	7	5.5	38.5	3	Other Granitoid
5	15	9	135	3	Mafic	31	6.5	5	32.5	1	Mafic
6	17.5	11	192.5	4	Basalt	32	8	5	40	3	Sm
7	17	10	170	3	DCtmg	33	7	6	42	2	Mafic
8	14	13	182	2	DCtmg	34	7	5	35	3	Other Dark Foliated
9	12	9.5	114	1	DCtmg	35	7.5	5.5	41.25	4	Single Granite
10	13	11	143	3	Basalt	36	7	5	35	4	Pegmatite
11	14	9	126	1	Other Granitoid	37	7	5	35	2	Single Granite
12	12	7	84	3	Src	38	9	6	54	4	Single Granite
13	12	6	72	4	Single Granite	39	6	4	24	3	Other Granitoid
14	10	6	60	2	DCtmg	40	7	5	35	2	Dl
15	11	7	77	4	Mafic	41	7	5.5	38.5	3	Other Granitoid
16	11	6.5	71.5	2	Mafic	42	6	5	30	3	Src
17	10	7.5	75	3	Other Granitoid	43	5	4	20	4	DCtmg
18	9	7	63	3	Dl	44	6	4.5	27	3	Single Granite
19	9	8	72	3	Single Granite	45	6.5	4	26	3	Sm
20	10	5.5	55	4	Dl	46	5.5	4	22	3	Basalt
21	9.5	7.5	71.25	4	Other Granitoid	47	5.5	5	27.5	3	Dl
22	9.5	7	66.5	4	Other Granitoid	48	5.5	4.5	24.75	3	DCtmg
23	10	6.5	65	3	Other Dark Foliated	49	5	3	15	2	Dl
24	9	6	54	2	Dl	50	5	4.5	22.5	4	DCtmg
25	10	5.5	55	3	Src	51	4.5	4	18	3	DCtmg
26	8.5	7	59.5	4	Single Granite	52	5.5	3.5	19.25	3	DCtmg

TABLE 4. The stone count from the Drifter pit.

#	Long	Intermedia	"Size"	Roundess	Lithology	#	Long	Intermedia	"Size"	Roundess	Lithology
1	9.5	7.5	71.25	1	Dl	26	12	8.5	102	1	Fine-Grain Schist
2	8.5	7	59.5	1	Dl	27	12	3	36	2	Dl
3	11	5	55	2	Other Dark Foliated	28	13	10	130	3	Fine-Grain Schist
4	11	8	88	1	Other Granitoid	29	13	12.5	162.5	1	Fine-Grain Schist
5	9	5.5	49.5	2	Src	30	14	7	98	2	Basalt
6	9	6	54	1	Dl	31	9	7	63	2	Pegmatite
7	9.5	6	57	2	Other Granitoid	32	7.5	5	37.5	3	Dwd
8	8	7.5	60	1	DCtmg	33	7	6.5	45.5	4	Ssf
9	10	7.5	75	3	Dl	34	7	5.5	38.5	2	Sr-c
10	9.5	6	57	1	Pegmatite	35	7	6	42	1	Fine-Grain Schist
11	8.5	6	51	2	Non-local anomoly	36	8	6	48	2	Basalt
12	12.5		0	3	Dl	37	7	4.5	31.5	3	Single Granite
13	8	8	64	1	Single Granite	38	7	5	35	2	Dl
14	9	6.5	58.5	3	Dl	39	6	3.5	21	3	Sr
15	11.5	8	92	1	Dl	40	7	5	35	2	Dl
16	10	7	70	3	Dl	41	6	5	30	1	Single Granite
17	9	7.5	67.5	1	Dl	42	6	4	24	1	Sr
18	10	8	80	2	Fine-Grain Schist	43	5	4	20	3	Single Granite
19	9	8	72	2	Dl	44	5	4	20	4	Ssf
20	9.5	6	57	2	Fine-Grain Schist	45	4.5	4	18	2	Dl
21	10	8	80	2	Src	46	14	12	168	3	Dl
22	7.5	5	37.5	2	Other Dark Foliated	47	16.5	11.5	189.75	2	Other Granitoid
23	10	7	70	3	Single Granite	48	17	14	238	1	Dl
24	12	9	108	1	Dl	49	18	12	216	2	Pegmatite
25	12	8.5	102	1	Dl	50	18	10	180	1	Other Granitoid

TABLE 5. The stone count form the Thumper 1 pit.

#	Long	Intermedia	"Size"	Roundess	Lithology	#	Long	Intermedia	"Size"	Roundess	Lithology
1	16	9	144	2	Src	26	10	10	100	3	Quartz
2	9.5	7	66.5	2	Other Granitoid	27	12	7	84	3	Src
3	11	9.5	104.5	1	Other Granitoid	28	12	10	120	1	Single Granite
4	10	8	80	2	Src	29	11	6	66	2	Other Granitoid
5	13	9	117	3	Sr-D	30	12	6.5	78	1	Mafic
6	12	8	96	2	Src	31	10.5	8.5	89.25	3	Src
7	12.5	11	137.5	4	DCtmg	32	12	7.5	90	4	Src
8	11	9.5	104.5	3	Pegmatite	33	10.5	6	63	2	Other Granitoid
9	14.5	8	116	2	Src	34	10	7	70	3	Src
10	16	9	144	4	Sr	35	10	5	50	2	Src
11	16	12.5	200	4	Pegmatite	36	9.5	6	57	3	Src
12	18.5	13.5	249.75	3	DCtmg	37	10	7.5	75	2	Sr-D
13	14.5	10	145	2	Src	38	8.5	7	59.5	2	Src
14	19	11	209	3	DCtmg	39	10	6	60	3	Src
15	15.5	10	155	2	Src	40	9	5	45	3	Sr
16	14	13	182	3	Sr	41	6.5	5.5	35.75	2	Sr-D
17	13	9	117	2	DCtmg	42	8.5	7.5	63.75	3	DCtmg-F
18	14	9	126	3	Src	43	6	4	24	3	Other Granitoid
19	8	5	40	2	Sr	44	7	4	28	2	Mafic
20	9	6	54	2	Src	45	6.5	5	32.5	3	Other Granitoid
21	9.5	8.5	80.75	3	Sr	46	7	6	42	3	Src
22	11	9	99	1	Other Granitoid	47	6	5	30	2	Dl
23	14	10	140	2	Src	48	5	5	25	1	Other Granitoid
24	14	8	112	2	Sr	49	6	5	30	3	Other Dark Foliated
25	12	8.5	102	1	Sr	50	7.5	5.5	41.25	4	Dctmg
						52	5.5	3.5	19.25	3	DCtmg

TABLE 6. The stone count from the Thumper 2 pit.

#	Long	Intermedia	"Size"	Roundess	Lithology	#	Long	Intermedia	"Size"	Roundess	Lithology
1	14	14	196	4	Src	27	8	7	56	2	Dl
2	22	17	374	4	Sr	28	7	6	42	2	Single Granite
3	13	10	130	4	Pegmatite	29	8	7	56	2	Dl
4	11	9	99	1	Other Granitoid	30	8	6	48	1	Basalt
5	9	7	63	3	Dl	31	7.5	5	37.5	3	Ssf
6	10	7	70	1	Pegmatite	32	8.5	6	51	4	Sr
7	10	7	70	2	Other Granitoid	33	7	6	42	2	Fine-grain Schist
8	8.5	7	59.5	2	Basalt	34	7	5.5	38.5	3	Basalt
9	11	5.5	60.5	3	Ssf	35	6	5	30	1	Other Granitoid
10	14	7	98	4	Ssf	36	8.5	5	42.5	2	Non-local anomoly
11	10	7	70	4	Non-local anomoly	37	6.5	5	32.5	2	Pegmatite
12	8.5	7	59.5	1	Non-local anomoly	38	6	5	30	3	Other Granitoid
13	8.5	6	51	3	Other Granitoid	39	7	4.5	31.5	3	Other Granitoid
14	7	5	35	2	Other Granitoid	40	7	4	28	2	Non-local anomoly
15	10.5	7	73.5	3	Fine-grain Schist	41	7	4	28	3	Other Granitoid
16	10	6	60	3	Ssf	42	8	5	40	3	Other Dark Foliated
17	8	7	56	2	Ssf	43	6	4	24	2	Dwd
18	8	6	48	2	Pegmatite	44	5	4	20	3	Basalt
19	9	7.5	67.5	2	Dl	45	5	4	20	2	Other Granitoid
20	9	4	36	3	Src	46	6	5	30	4	Other Granitoid
21	9	6.5	58.5	3	Pegmatite	47	6.5	5	32.5	3	Other Granitoid
22	9	5.5	49.5	2	Other Granitoid	48	6	4.5	27	4	Quartz
23	8	6	48	1	Single Granite	49	6.5	4.5	29.25	3	Sm
24	8.5	5	42.5	2	Other Granitoid	50	5.5	3.5	19.25	2	Dl
25	8	6.5	52	3	Pegmatite	51	5.5	4	22	2	Other Granitoid
26	7	6.5	45.5	1	Basalt	52	4.5	3	13.5	2	Other Granitoid
						53	5	5	25	4	Pegmatite

3.2 Glacier Reconstruction

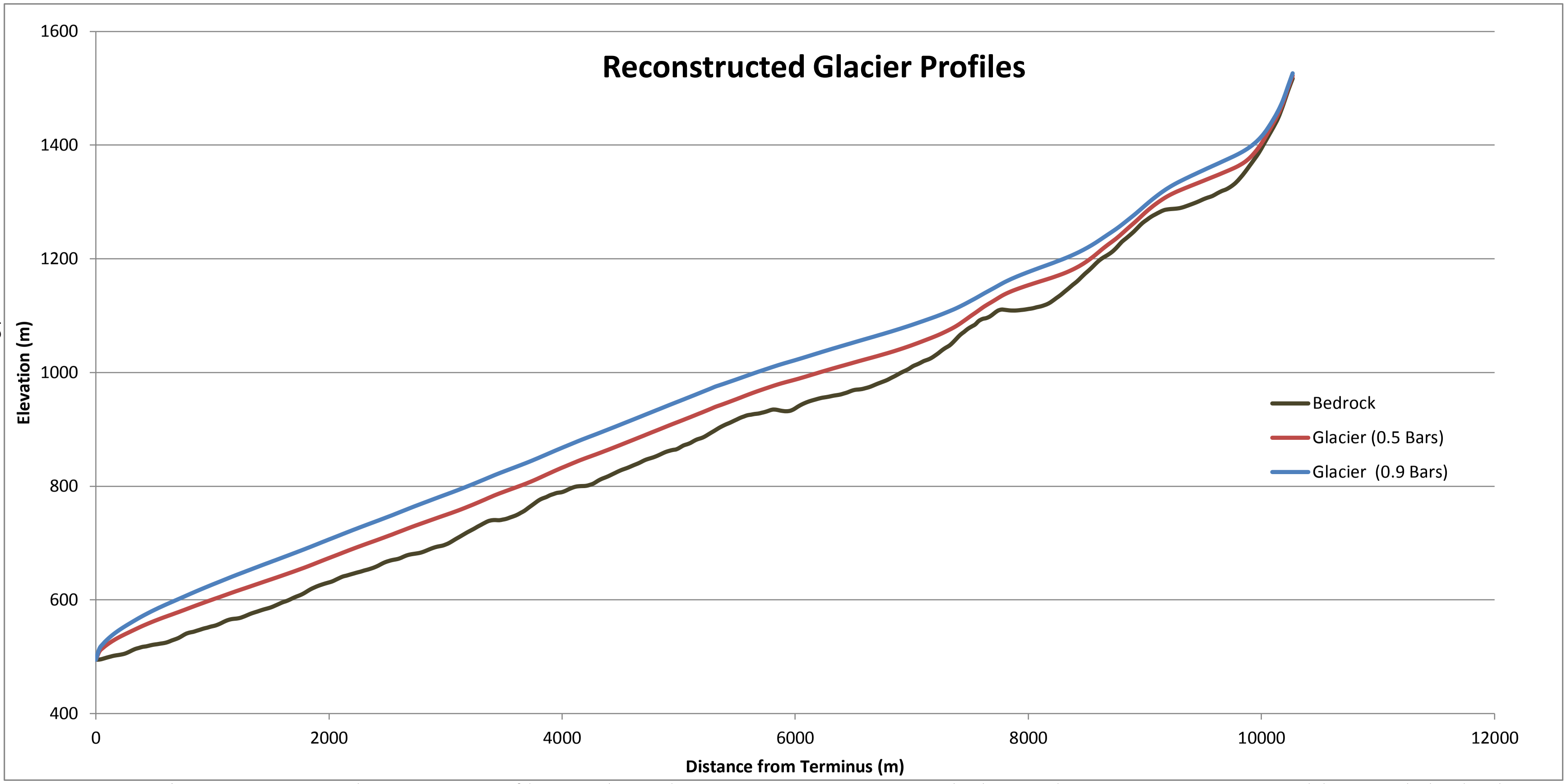

FIGURE 15. The reconstructed ice mass profiles, with 0.5 bar reconstruction in red, the 0.9 bar reconstruction in blue, and the bed in brown.

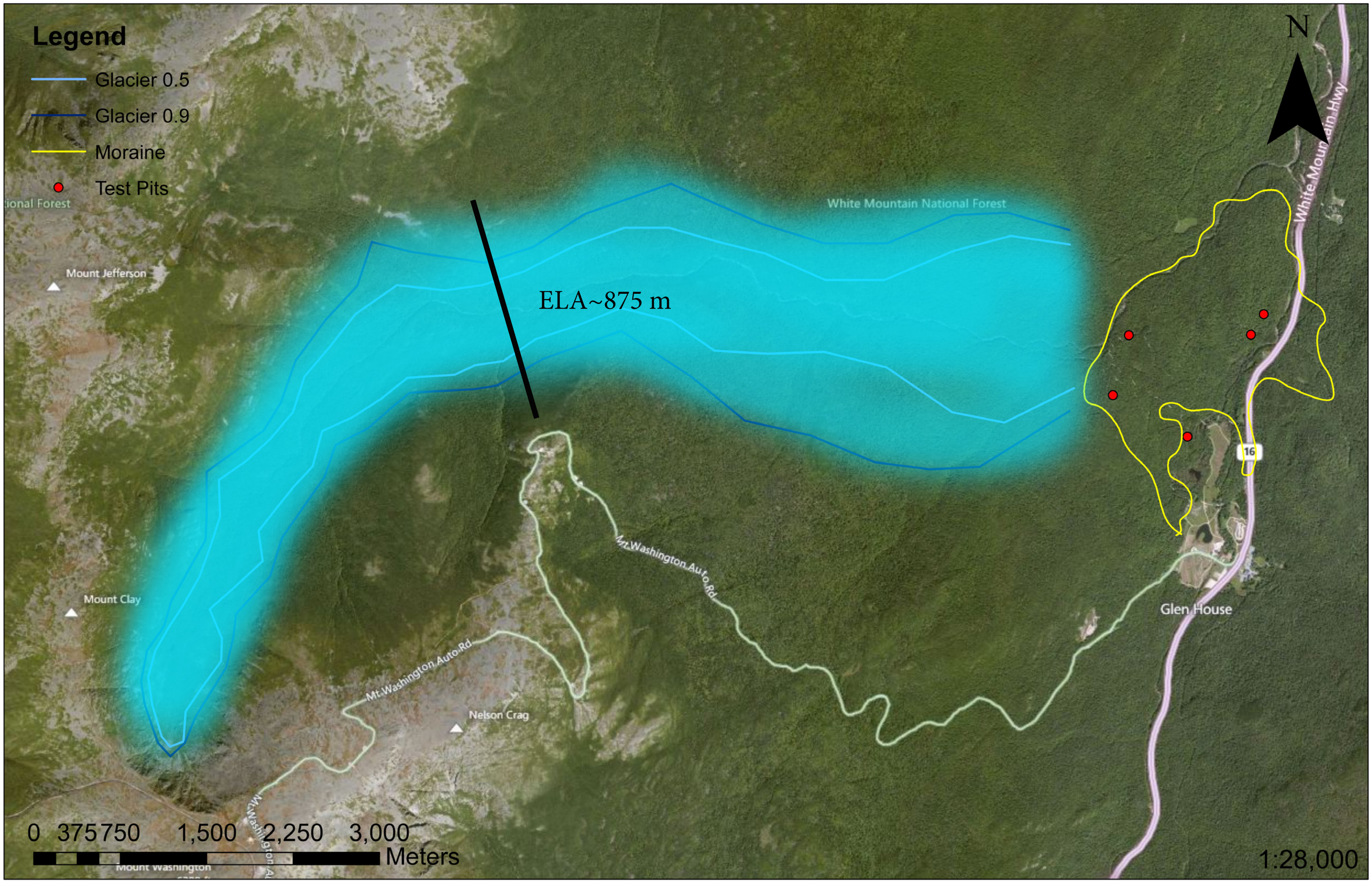

FIGURE 16. The reconstructed glacier using the 0.9 bar recontruction. Note the test pits (red dots), the outline of the landform (yellow), and the ELA (black).

The glacier was reconstructed using 0.5 bar and 0.9 bar values for basal shear stress in order to get a minimum and maximum value for ice thickness. This ice thickness, on average, was about 50 and 100 m, respective to the 0.5 ad 0.9 bar reconstructions, but did vary by as much as 25 m depending on the slope of the bed below the ice (Figure 15) . After constraining the ice mass using 30 cross sections, the reconstructed ice mass was plotted on a topographic map in order to determine a paleo-ELA.

3.2.1 Paleo-ELA

The elevation of the toe of both reconstructed glaciers was 495 m. The headwall altitude of the glacier reconstructed using 0.5 bars of shear stress was 1,364 m. The headwall altitude of the glacier reconstructed using 1.7 bars of shear stress was 1,474 m. Using the THAR method, the paleo-ELA of the glacier reconstructed using 0.5 bars was 822 ± 22 m. The paleo-ELA of the glacier reconstructed using 1.7 bars was 862 ± 25 m. Using the AAR method the produced paleo-ELAs was 860 m for the 0.5 bar glacier, and 910 m for the 1.7 bar glacier.

TABLE 7. The results of the various ELA reconstruction methods.

Glacier	THAR (m)	AAR (m)	Avg (m)
0.5 Bars	822 ± 22	860	841
0.9 Bars	842 ± 25	900	871

Discussion

4.1 Stone Counts

The stone counts show a great deal of variability between proximal pits for all rock types, but do not lack organization. After the rock types are separated by source location (cirque, north, adjacent, erratic; Figure 17, 18) some interesting patterns appear. The percentage of erratic stones ranged from 26% to 57%, similar to those found by Goldthwait (1970), which was 20% to 60%, and higher than those found by Waitt and Davis (1988), which was 32% to 48%, although it is worth noting the latter stone counts were taken on the northern section of the Presidential Range, and the proximal lithologies differed slightly. Relatively high percentages of erratic clasts in the landform can most likely be attributed to residual till from the Laurentide Ice Sheet left within the cirque. This till would be eroded before the bedrock in the cirque and would therefore make up a significant percentage of the terminal moraine if a cirque glacier were reactivated. Goldthwait (1970) claimed there would not be enough residual till to constitute such a large percentage, but it is possible that till could concentrate in a cirque as deep as the Great Gulf. The adjacent rocks, Rangely formation, both migmatized and unmigmatized, are found both north of the feature and on the cirque side of the feature, meaning they could have been deposited by both a cirque glacier and the continental ice sheet. It is therefore necessary to examine the percentage of cirque rocks as compared to northerly rocks explicitly, and factor in the percentage of adjacent rocks as supplemental to this comparison.

A till fabric was not observed in any of the test pits, nor were any patterns in the shape and size of the clasts relative to pit location found, aside from the Libby pit, which will be discussed shortly. However, the lack of lodgment till can determined from a lack of bullet-shaped clasts and striated clasts, however, this lack of lodgment till could be attributed to the presence of residual till. Unfortunately, members of this residual population could also be local lithologies, so it is therefore difficult to isolate the residual population without removing stones relevant to the study. It should be noted that the Smalls Falls and Madrid Formations as well as the pegmatite population, all of which were considered local to the cirque, were more angular than other lithologies. This angularity could be attributed to their proximity to the landform and the limited distance they would have travelled before deposition, but could easily be a product of the lithological composition or whether the stones were carried englacially.

The Libby pit (Figure 17) is perhaps the most interesting at first glance, being composed of 62% rocks of northern provenance, mainly small, well-rounded binary granites (DCtmg). The high percentage of these northern rocks when considered with the pits southerly location might indicate that the feature could have been deposited by a readvance of the continental ice sheet from the north. However, the location of the pit relative to the location of the proposed terminal moraine as mapped by Fowler (2011) shows that the pit lies within sediments outside the boundary of the landform as mapped. The pit lies in a very flat area as compared to the hummocky, variable terrain found on the landform itself, indicating that the landform does not extend to the location of the pit. The average roundness and size of the clasts in the pit (Table 2) could also indicate that the clasts have undergone significantly more weathering than those found in the four other pits. For these reasons, the Libby pit was not factored in with the rest of the pits. Rather, the pit is a good example of sediments found around the deposit, and what we might expect to see within the mapped landform if it were a product of a readvance of the continental ice sheet.

The Wilding and Drifter pits (Figure 17, tables 3 and 4, respectively) were the most proximal to the cirque and is where you would expect to see the highest percentage of cirque clasts, as is the case with the Drifter pit, which contained 47% cirque rocks compared to 2% northerly rocks, as well as a low percentage of adjacent rocks. However, the Wilding pit just a few hundred meters south only contained 21% cirque rocks as compared to 17% northerly rocks, and 10% adjacent rocks. The most reasonable explanation would be that rocks of northern origin are represented in the residual till stone population that produced the high percentage of erratic stones, and that some percentage of northern rocks would be present in a terminal moraine deposited by a local alpine glacier in the Great Gulf.

Lastly, the Thumper 1 and 2 pits (Figure 17, tables 5 and 6, respectively), found on the northeastern section of the feature are the most proximal to the northerly and adjacent rocks, and would in theory contain higher percentages of these rocks than those found on the other side of the feature. Thumper 1 contained only 6% cirque rocks, compared to 12% of northerly rocks. Interestingly, the pit was composed of 56% adjacent rocks, and is perhaps the best argument against a reactivated cirque glacier. However, as noted earlier, the adjacent rocks also have the greatest amount of uncertainty associated with them, as they could have been deposited by both a cirque glacier and the continental ice sheet, thus Thumper 1 does not assist in differentiating the origin of the landform. The Thumper 2 pit, found just meters north of Thumper 1, was much better defined, containing 36% rocks of cirque origin, as compared to 0% of northerly rocks, and 7% adjacent rocks. For these reasons, Thumper 2 stones could be considered the best evidence for a reactivated cirque glacier.

When the four relevant pits are grouped together (Figure 18), the results are more conclusive. Rocks of cirque origin composed 26% of the total as compared to 7% northerly rocks, and 19% adjacent rocks. This considerably higher percentage of cirque rocks as compared to northerly rocks supports the idea that the feature in question was deposited by an active ice mass in the Great Gulf as opposed to a readvance of the continental ice sheet from the north. While the percentage of adjacent rocks is significant, their origin is uncertain and therefore not regarded with the same weight as rocks from the cirque and

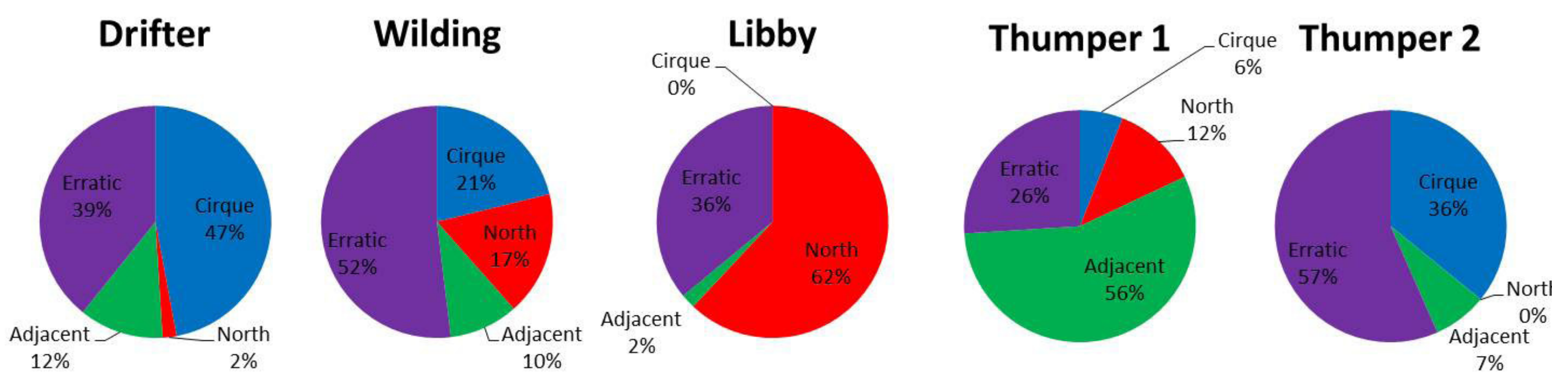

FIGURE 17. (Above) The source-classified results from the stone counts.

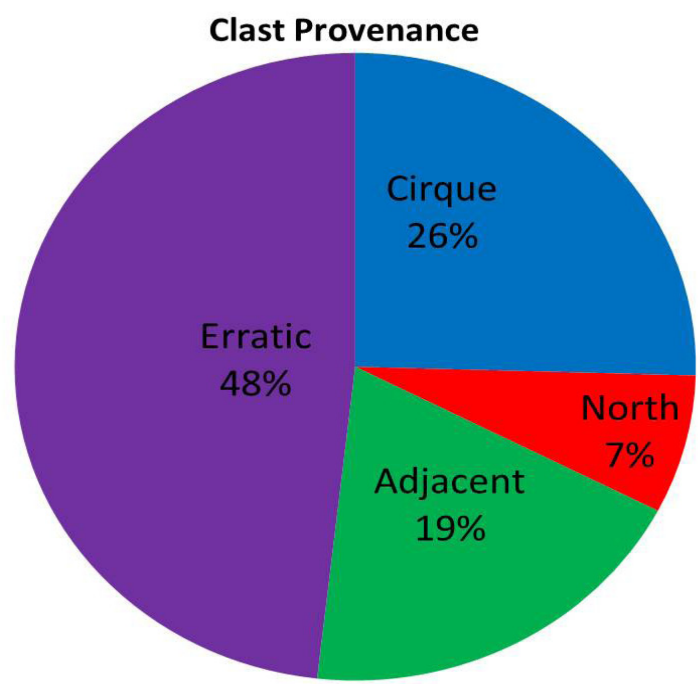

FIGURE 18. (Right) The compiled, source-classified results from the stone counts, excluding Libby.

the north.

After considering these stone lithology factors, the landform could be composed of flow, or collapse-emplaced, till, often found at the snouts of alpine glaciers. The deposit is characterized by a lack of till fabric and orientation, and is instead formed by a depositional process that disregards the direction of glacial flow (Kruger and Marcussen, 1976). While it is possible that the sediments are well-sorted, the depth of the test pits does not allow for a definitive conclusion to be made. However the landform in question can be distinguished from a colluvial deposit based on its more pronounced topography when compared to colluvial features found to the north (Fowler, 1984). The colluvial feature identified beyond the mouth of King Ravine studied by Fowler (1984) does not have topographical relief as compared to the valley immediately upslope. The landform at the mouth of the Great Gulf, however, has a relief of almost 25 m from the valley immediately upslope and contains approximately 0.55 cubic kilometers of material. It is all the more significant that the only other topographically pronounced deposit in the area, an alluvial fan located 10 km to the northwest, reaches a maximum relief of 12 m on a single, isolated landform (Fowler, 2011).

4.2 Climatic Implications of a Local Cirque Glacier

If we assume that the landform at the mouth of the Great Gulf cirque is a terminal moraine associated with a reactivation of an ice mass in the Great Gulf, what would that indicate about the climate at that time? The climate conditions necessary to allow for such a glacier would have to be significantly colder than those found today, as there is no glacier present. Instead, we can use reconstructed glacier profiles to constrain past climate conditions in the Great Gulf during an ambiguous period of climate history. In order for a glacier to have existed, the paleoclimate must have reached favorable conditions at the ELA of the reconstructed glacier, around 875 m.

Aside from solely relying on the reconstructed paleo-ELAs, the cirque geometry should also be taken into account when evaluating the existence of a cirque glacier. Summer insolation was considerably high immediately after the LGM than it is today, around 40 w/m^2 higher than contemporary values (Berger & Loutre, 1991). However, the northerly aspect of the cirque is the most favorable to limit the effects of such an elevated value (Evans, 2006). The depth of the cirque also promotes to accumulation of windblown snow, allowing for snow depths that far exceed the measured amounts of precipitation (Haven, 1960) as well as a lower ELA (Lie et al., 2003). So, although the minimum climate conditions may not have been met, both the sheltering effect from radiation attributed to the aspect of the cirque, as well as the accumulation of wind-blown snow attributed to the depth of the cirque, would only help to encourage the growth of a glacier during the brief periods of cooling (Humlum, 1997).

The reconstructed paleo-ELA of the Great Gulf glacier provides a means for evaluating the difference between the climate today, and the climate at the time of glacial reactivation. For a glacier to exist in the Great Gulf, the climate at the ELA would need to be significantly colder with an increase in precipitation to promote the growth of an ice mass. Using the calculated paleo-ELAs and contemporary climate information, it can be said that the mean annual summer temperature today at the former ELA is about 14.4 °C and an annual precipitation of about 2,600 mm (MWO, 2011). These conditions are plotted (Figure 19) with the global data set from Ohmura et al. (1992) and the difference between current climate and climate capable of producing a glacier can be seen. Figure 19 compares the average summer temperature to the annual precipitation at the ELA of dozens of glaciers. It is important to note that from figure 18 we can see the amount of variability that can be associated with climate and still allow for a glacier to exist. If a cirque glacier were to exist in the Great Gulf, it would have experienced relatively high summer temperatures and required increased amounts of precipitation, as the magnitude

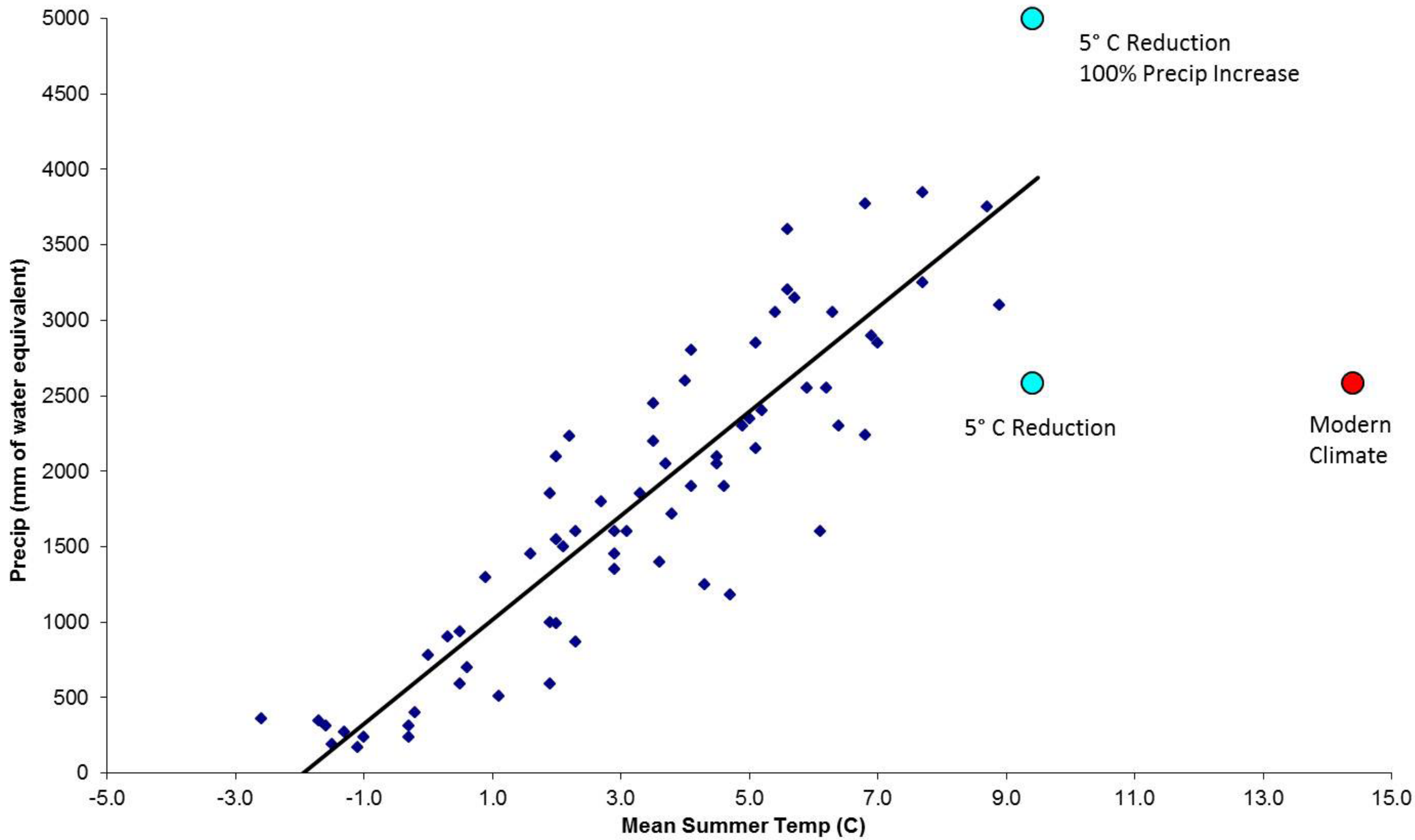

FIGURE 19. Data compiled from Ohmura et al. (1992) with modern-day climate (red), as well as 5 degree Celcius reductions, one with a 100% increase in annual precipitation (blue), shown.

of the temperature reduction without increased precipitation would be unreasonable given regional proxies. Environments with average summer temperatures as high as ~10° C can still support a glacier with the necessary amount of precipitation, especially when considering the cirque geometry, as discussed previously. Areas with a maritime climate such as New Zealand can support glaciers because of large amounts of annual precipitation (Ohmura et al., 1992). However, disregarding the geometry, the Ohmura et al. (1992) data would indicate that without an increase in precipitation, a temperature decrease of around 8° C would be required, and without a decrease in temperature an increase in annual precipitation of about 3,500 mm would be required to maintain a cirque glacier in the Great Gulf. The latter value could perhaps be reached when effects from the cirque aspect and depth are considered.

The two most likely time periods for the existence of a local glacier after the LGM are the Older and Younger Dryas periods (Figure 20), which occurred roughly 14,000 and 13,000 cal ^{14}C years BP, respectively. While proxies for the Older Dryas are not as well defined in the area, the Littleton-Bethlehem readvance was attributed to the period by constraining the ages using radiocarbon dates (Thompson et al., 1999). The readvance was a lobe of the continental ice sheet that advanced south during this cooling period and left behind a moraine complex running parallel to the southern margin of the ice sheet. This readvance occurred approximately 25 kilometers to the northwest of the Great Gulf, so it perhaps an icemass could have grown in the cirque at such a time. It is also possible that a residual stagnant icemass left from the continental ice sheet could have been reactivated during such a cooling period. There is also the possibility of a readvance of a lobe of the continental ice sheet in the valley from the north, but we would expect to see a much higher population of northerly-derived rocks in the test pits from the possible terminal moraine.

The climate in the region during the Younger Dryas is more constrained than the

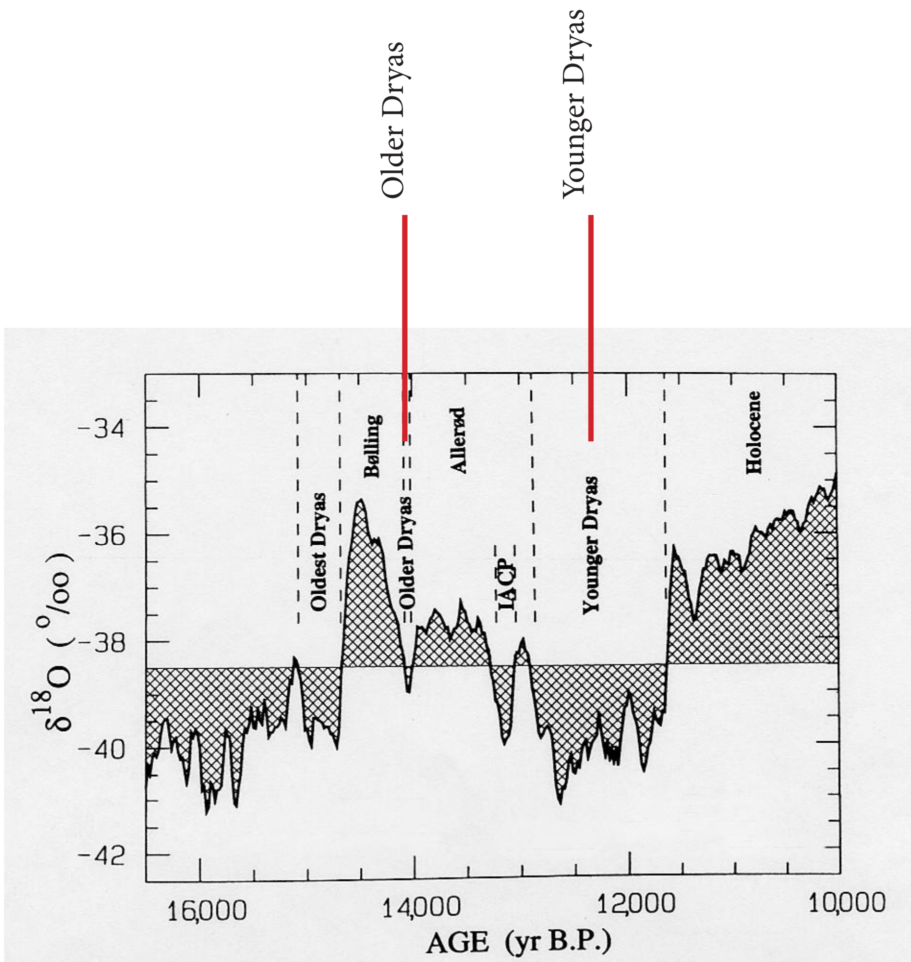

FIGURE 20. Record from the GISP 2 ice core showing oxygen isotope records that roughly correspond to regional temperatures. Note the Younger Dryas and Older Dryas climate reversals, adapted from GISP2.

Older Dryas. Cwynar and Spear (2001) used pollen from pond sediments to estimate a temperature reduction of at least 5° C in the area at the time by examining the associated plant species and their climate tendencies. Addtionally, Cwynar & Levesque (1995) found that surface water temperatures in the area fell as much as 13° attributed to the Younger Dryas cooling using the distribution and abundance of midge flies from pond sediments. This reduction, coupled with a poorly constrained increase in precipitation (Thorson and Schile, 1995; Bromwich et al., 2005), as determined using changes in eolian regimes, could have easily created the necessary climate conditions to reactivate a glacier in the Great Gulf.

While both these periods were colder than modern climate, they do not meet the previously established climate conditions based on ELA reconstructions necessary to promote the growth of an icemass in the Great Gulf. ELA reconstructions suggest that if there was local alpine glaciation during one of these two cold periods, the magnitude of cooling was larger than previously thought, or there was a significant increase in precipitation. Ground–penetrating radar and sediment cores from ponds around the White Mountains from Shuman et al. (2005) indicate that these periods could have been wetter than previously thought. Although not well constrained, reconstructed lake-level estimates indicate that annual precipitation in the White Mountains was greater than current levels. However, conclusions of moisture-balance in the White Mountains during the late-Pleistocene are still somewhat open-ended, as these reconstructed lake levels cannot constrain levels above their contemporary level as erosive processes can expunge evidence.

Further support for the growth or re-establishment of a local glacier on Mount Washington is provided by several studies that have documented the existence of local alpine glaciers in other regions of North America after the recession of the Laurentide Ice Sheet. Cirque glaciers in the Rocky Mountains experienced fluctuation associated with cooling periods after the recession of the continental ice sheet from the regions for over a millennium until around 12,000 cal ^{14}C years BP (Clark and Gillespie, 1997; Osborn and Gerloff, 1997). Even in Nova Scotia, local glaciers had a documented advance as a result of Younger Dryas cooling period (Stea and Mott, 1989), demonstrating that these late-Pleistocene climate reversals were capable of reactivating local glaciations for centuries, although exact reductions in temperature are unknown. However, glaciers in the Sierra Nevada did not undergo an advance during the Younger Dryas cooling period due to high temperatures and/or a lack of precipitation (Clark and Gillespie, 1997), which illustrates the amount of regional variability associated with the climate during this period.

4.3 Possible Sources of Uncertainty

The first major source of uncertainty in the study was associated with the stone counts. DCtmg, the only binary granite in the immediate area around the landform, served as the sole lithology that was to derived from the north. While the Rangeley Formation stones were not attributed to either the north or the cirque, lithologies considered cirque rocks, specifically bands of the Littleton, Madrid, and Smalls Falls Formations, are found to the north of the landform, but were attributed to the cirque as serve as the primary indicator in the cirque, and is found in much lower abundance to the north. Unfortunately, it would be difficult to model a readvance of a tongue of the continental ice sheet down the Peabody River valley as it would the location of the southern margin of the continental ice sheet is not well constrained, aside from the Littleton-Bethlehem moraine complex.

Another large source of error can be derived from the model used to reconstruct alpine glaciers. In Benn & Hulton (2010) the initially calculated ice thickness is constrained by some thickness indicator, such as medial moraines or scour marks. This constraint, with the bed slope, allows for the determination of the approximate shear stress and more accurately reconstruct the ice thickness. Unfortunately at our study site, there are no such thickness indicators aside from the landform in question. Instead, two extreme values (0.5 and 1.7 bars) were used to establish minimum and maximum ice profiles. However, this uncertainty only yielded a 50m difference in the determined paleo-ELA, an altitude disparity that would only amount to a difference in temperature on the order of a few tenths of a degree.

Another source of uncertainty is associated with the contemporary climate conditions at the paleo-ELA being calculated using Mt. Washington summit data and a regional lapse rate developed by Cwynar & Spear (2001) of 6.2° C/km. While this rate is perfectly acceptable, the exact temperature and weather dynamics of the Great Gulf are complicated, as Mt. Washington has some of the most extreme climate in the New England. Deviations from the established atmospheric lapse rate would not be unexpected, especially during Late-Pleistocene climate reversals.

Finally, determining the age of the possible terminal moraine is difficult as the landform does not lend well to accurate dating methods and the local proxies are not well constrained. While surface exposure dating and pond sediments have been used to determine some ages in the area, these methods are not well constrained and should be the focus of future work in the area.

Conclusion

5.1 Conclusions

The results of the stone counts, specifically the percentage of clasts derived from the cirque as compared to those derived from the north, could indicate that the proposed terminal moraine in question is of cirque origin. The pronounced topography of the landform when compared to similar features found around the area suggests that the landform is neither alluvial, nor colluvial in origin, indicating a glacial deposition as a likely source.

After reconstructing a cirque glacier capable of depositing a moraine on the valley floor, an ELA of approximately 875 m was determined. After determining the contemporary climate at the ELA, the minimum temperature reductions and precipitation increases necessary to promote the growth of a cirque glacier were calculated to be around 8° C and/or 3,500 mm. The local climate of the late-Pleistocene, although colder and wetter at times, is not well constrained, and it is difficult to conclude if necessary climate conditions could have been met. So, it is uncertain whether there was a cirque glacier, or not, or that the temperature and/or annual precipitation amounts currently attributed to these climate reversals in the White Mountains are underestimates.

5.2 Future Work

Future work in the area should first and foremost include additional stone counts spread across the landform and should also include samples from till derived from the continental ice sheet. Although the data from this study were conclusive, the disparity between the compositions of proximal test pits would suggest that there is a great deal of variability within the composition of the landform. More test pits across the landform would allow for a comprehensive look into its composition and origin. Sampling from till derived from the continental ice sheet would provide some standard with which to compare the stone counts from the landform. Refinement of the lithological analysis would also help distinguish the origins of the landform. While dividing the stone counts in the test pits into basic geographical origins (i.e. cirque, north), identifying exact lithologies and their representative sources could enhance the quality of the stone counts.

Better constraints on the late Pleistocene climate in the area would also help in assessing whether or not a cirque glacier could have existed after the recession of the continental ice sheet. The most promising source of data could be from Spaulding Lake, a small body of water directly below the headwall of the Great Gulf. While more reconnaissance must be done, sediments from the lake bottom could provide organic material for radiocarbon dating and proxies for temperature and moisture balance in the Great Gulf during the late-Pleistocene.

Finally, the work of Fowler (2011) also identified a feature partway up the Great Gulf below Nelson Crag as a possible recessional moraine associated with a reactivated local glacier in the cirque. Located on the inner bend of this study's reconstructed glacier, the landform does merit further investigation as its origins could further constrain the climate of the late Pleistocene in the White Mountains.

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