COMPOSITION, MORPHOLOGY, AND GENESIS OF A MORAINE-LIKE FEATURE IN THE MILLER BROOK VALLEY, VERMONT

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ABSTRACT: We tested the hypothesis advanced by Wagner (1970) and contested by others (Waitt and Davis 1988) that a long, arcuate ridge in the Miller Brook valley, northwestern Vermont, is the lateral and end moraine of a post-icesheet alpine glacier. To evaluate this hypothesis, we mapped the feature at 1:2,500 scale with 2 m contours and we examined soil profiles for ten soil pits on and near the feature. Matrix grain size, clast lithology and orientation were quantified for some pits. All pits located on the moraine contain unsorted, unbedded, loose, sandy diamict with subangular clasts, 13% of which are erratic. We found no evidence of post-glacial fluvial erosion along the margin of the ridge and conclude that the feature is a moraine.

To evaluate the climatic potential for post-icesheet alpine glaciation, we estimated the equilibrium-line altitude (ELA) of a hypothetical alpine glacier in the Miller Brook "cirque" utilizing an accumulation-area ratio of 0.65. We compared this ELA (480 m) to an estimate of the contemporary July freezing isotherm (3050 m) and estimated the summer temperature depression necessary to support an alpine glacier. Our calculations indicate that summer temperatures must drop about 14° C to support an alpine glacier in the Miller Brook valley. Despite several potential sources of inaccuracy, the large discrepancy between our estimates and paleo-climatic evidence from other research suggests that this moraine was deposited by a lobe of the waning continental icesheet; our work does not support Wagner's assertion that this moraine is the deposit of an independent mountain glacier.

INTRODUCTION

Glacial landforms provide valuable information about paleoclimate, but valid climatic inferences are dependent upon accurate interpretations of landform genesis. In this paper, we describe one landform that has been interpreted as having important implications for understanding late-Pleistocene warming trends and the variability of New England's climate during deglaciation.

The Miller Brook "moraine" is a ridge located on the south side of the Miller Brook valley near Lake Mansfield, Lamoille County, Vermont (Fig. 1). Miller Brook flows eastward from Nebraska Notch (580 m at sea level), on the crest of the Green Mountains, to its confluence with the Little River (185 m at sea level). Lake Mansfield (345 m above sea level) is artificially impounded and occupies a broad, low-relief portion of the Miller Brook valley that is surrounded by steep, high-relief mountains (Fig. 1). Immediately downstream from the Lake Mansfield dam, a free-standing ridge parallels the south side of the valley until it turns and partially crosses the valley. Wagner (1970) briefly described these landforms and interpreted the bowl-shaped valley and Lake Mansfield respectively as cirque and tarn and the ridges as lateral and end moraines. He suggested that the moraines were produced by a small alpine glacier occupying the cirque during or shortly after the local retreat of the Laurentide icesheet (13-14,000 $_{14}$C years ago; Denton and Hughes 1981). This interpretation, like all discussions of post-icesheet glaciation, has engendered widespread debate (Waitt and Davis 1988, Table 1, p. 497), largely because pollen records (Davis et al. 1980) and other evidence suggest a period of steady warming and consequently rapid icesheet retreat in New England at the same time that such putative alpine glaciers would have formed.

Although the Miller Brook valley has been discussed frequently in the debate over post-icesheet glaciation in Vermont, no work has described in detail the moraine-like feature (hereafter "the ridge") we consider here. Wagner (1970) located the ridge with a crudely drawn map and described its gross morphology, while Connally (1971) referred to it with no description at all. In his argument against regional alpine glaciation, Stewart (1971) ignored the ridge, and Waitt and Davis (1988, Fig. 6, p. 510) acknowledged but incorrectly located the ridge in their discussion and map of the Miller Brook valley. In this paper, we present the first detailed study of the morphology and composition of this landform. To evaluate Wagner's hypothesis that this ridge was deposited by an alpine glacier, we consider three questions : i) Is the ridge composed of sediments consistent with deposition by ice? ii) Is the ridge a constructional or erosional feature? iii) Was the climate of northern New England capable of sustaining alpine glaciation at the altitude of the Miller Brook valley soon after local retreat of the Laurentide icesheet?

METHODS

The ridge originates 85 m east of the Lake Mansfield dam (Fig. 2) and continues downstream for approximately 800 m. From a distance, mature hemlock and spruce blur the distinction between the ridge and the main slope of the adjoining hillside, but a walk along the trail that roughly follows the crest of the landform clearly reveals a connected series of ridges up to 24 m above the valley bottom and as much as 60 m wide at their base. Adjacent to the upper marsh and bog (Fig. 2) the ridge is distinctly separated from the steep south side of the valley. In other places the ridge is separated from the valley side by only a low-relief linear depression (e.g. SW of the pond and near soil pit T3M) or is discernible only by a low-relief step along an otherwise steep slope (e.g. 50 m SE of soil pit T3M). Elevations along the ridge crest vary from 362 m to 344 m.

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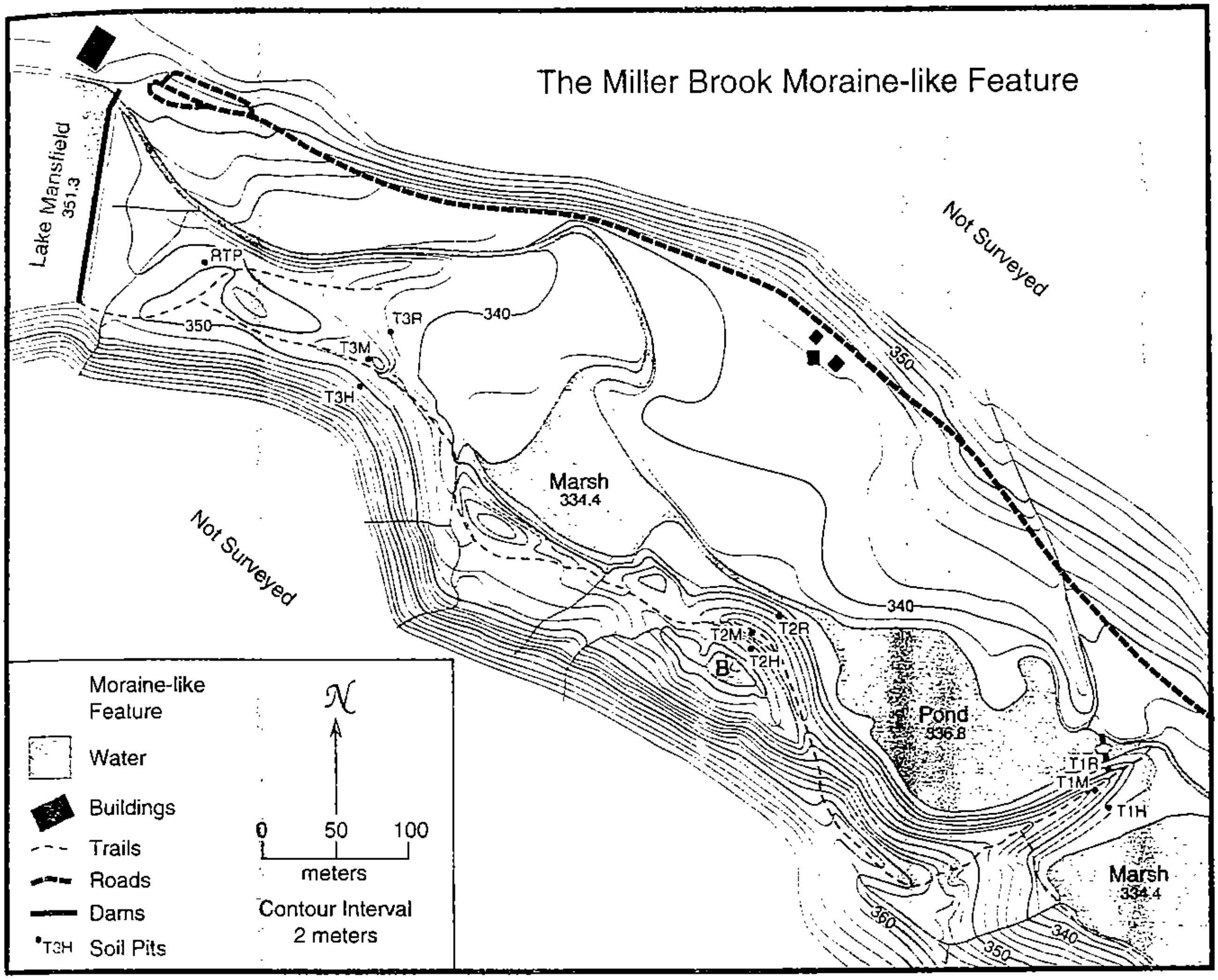

Figure 2. Detailed topographic map of the moraine-like feature (shaded in gray), Lamoille County, north-central VT. Contours are hand-drawn from 500 points surveyed in October and November, 1995. Locations of soil pits are shown and labeled, roads and trails are indicated by dashed lines, and a bog ("B") described in the text is shown. All watercourses shown in gray, except for Miller Brook and its associated wetlands, are ephemeral streams shown for clarity. Elevations, in meters, are given relative to a local United States Geological Survey benchmark.

technique described by Porter (1968, 1970) and Hawkins (1985). The upper altitude of this hypothetical glacier is limited by steep cliffs in the upper valley; the lower altitude is defined by the ridge. Lateral trimlines are not apparent on either side of the valley, so our reconstruction of the lateral glacier margin and glacier contours was inferred from the known altitude limits and topography. Steep valley walls like those in the Miller Brook valley minimize the sensitivity of calculated surface area to errors in estimating a glacier's lateral margin (Porter 1975), but ELA may be more sensitive to these errors. After reconstructing the glacier topography, we calculated the area of the glacier's accumulation zone. Accumulation area ratios of modern valley glaciers commonly range from 0.5 to 0.8 (Meier and Post 1962); we used a ratio of 0.65, generally considered characteristic for steady-state, temperate valley glaciers (Meierding 1982; Leonard 1984). Starting at the highest altitude of the reconstructed glacier, the area between glacier-surface contours was measured with a digitizing tablet, and ELA was approximated by finding the altitude above which cumulative measured area equaled 65% of the total glacier surface.

Because ELA is sensitive to summer temperatures, the July freezing isotherm (JFI) is sometimes used as an approximation of ELA (Leopold 1951; Richmond 1965; Ohmura et al. 1992). In Halifax, Nova Scotia, which is similar in latitude and climate to the Miller Brook valley, the modern free atmosphere JFI is 3048 m (Federal Climate Complex 1995). Using the lapse rate (5.3° C/1000 m; Spear 1989) measured at Mount Washington, in the nearby White Mountains, we then determined the summer temperature depression necessary for maintenance of a valley glacier by calculating the difference between contemporary JFI and estimated ELA of a post-icesheet glacier and dividing the result by lapse rate.

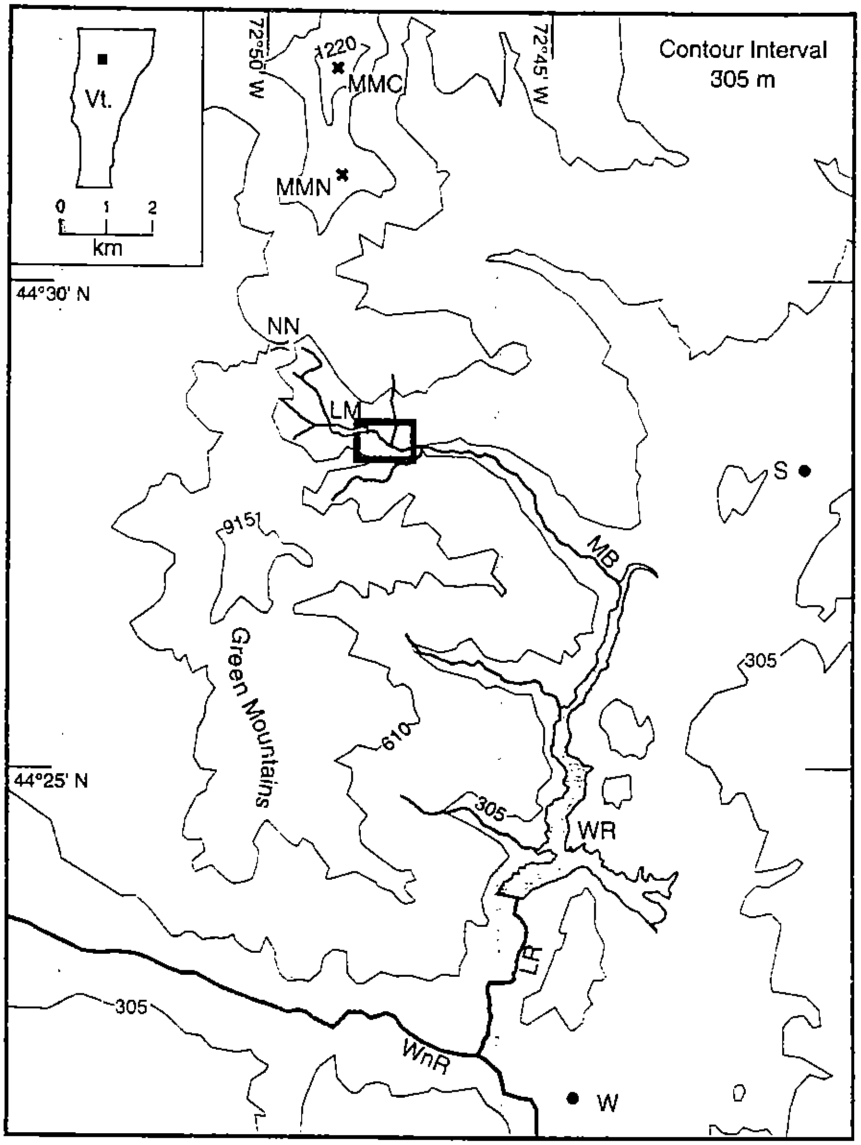

Figure 1. General location of the Miller Brook valley, Lamoille County, north-central Vermont. Locations of Nebraska Notch (NN), Miller Brook (MB), Lake Mansfield (LM), the Mount Mansfield Nose (MMN) and Chin (MMC), the Little River (LR), Waterbury Reservoir (WR), the Winooski River (WnR), and the towns of Waterbury (W) and Stowe (S) are noted. Shaded rectangle indicates the location of the moraine-like feature mapped in Fig. 2.

We surveyed the ridge with a Pentax SC-2 total station, collecting data from 500 points along the ridge and its surroundings. Mapping was completed by hand, using a scale of 1:2,500 and a contour interval of 2 meters (Fig. 2). Metric elevations were determined relative to the nearest benchmark: 1127' (44°28' N 72°48' W; United States Geological Survey 1976).

We dug ten soil pits (~1.0 m² by 0.8 to 2.0 m deep) on and around the ridge. Seven pits were located directly on the feature; one additional pit was located on a hillside south of the ridge, and two pits were located on the valley floor north of the ridge (Fig. 2). Depth, stratigraphy, texture, color, and soil development were recorded for each pit.

We collected additional information from unweathered parent material in some pits. Samples from three pits on the ridge (T2H, T2M, T2R; Fig. 2) and from an exposure of lodgement till in a stream bank near the dam were dried to constant weight and sieved for grain-size analysis. Strike and dip of 31 clasts from one pit (T2H) were measured. To determine the proportion of erratic clasts in the ridge, pebbles and cobbles collected from pit T1M (233 clasts), pit T1H (132 clasts), pit T2H (100 clasts), and pit T2M (9 clasts) were identified as either local or erratic.

To evaluate the climatic potential for post-icesheet alpine glaciation in the Miller Brook valley, we determined the approximate equilibrium-line altitude (ELA) of a hypothetical cirque glacier using the accumulation area ratio (AAR)

RESULTS AND DISCUSSION

Composition

Two typical soil pit profiles (Fig. 3) show that the predominant material exposed consists of unstratified and unsorted sediment. Variably sized (1-100 cm diameter) subangular clasts were supported by a silty loam, sandy loam, silty sand, or sand matrix. Cumulative grain-size distributions of the matrix from three samples from the ridge and one sample taken from compact lodgement till exposed in a nearby stream bank show the wide grain-size distribution in all samples and the higher percentage of fines in lodgement till (Fig. 4). Pebble counts from four soil pits on the ridge (Table 1) show that 11-14% of sampled clasts are erratic. Complete soil pit data are summarized in Table 2.

The predominant material exposed in these soil pits exhibits all three primary traits of till (Goldthwait 1971): i) a lack of sorting (indicated by boulders and pebbles supported within a fine matrix), ii) a homogeneous mixture without regular bedding, and iii) a mixture of lithologies. Only one of the soil pits located directly on the ridge differed from this description: Pit T1R, located 2 m above Miller Brook, revealed a distinct contact at 117 cm depth between an upper horizon of unstratified sandy loam with subangular clasts and a lower horizon of sorted gravelly sand with 1 cm diameter subrounded pebbles (Fig. 3). Unsorted diamict found at both

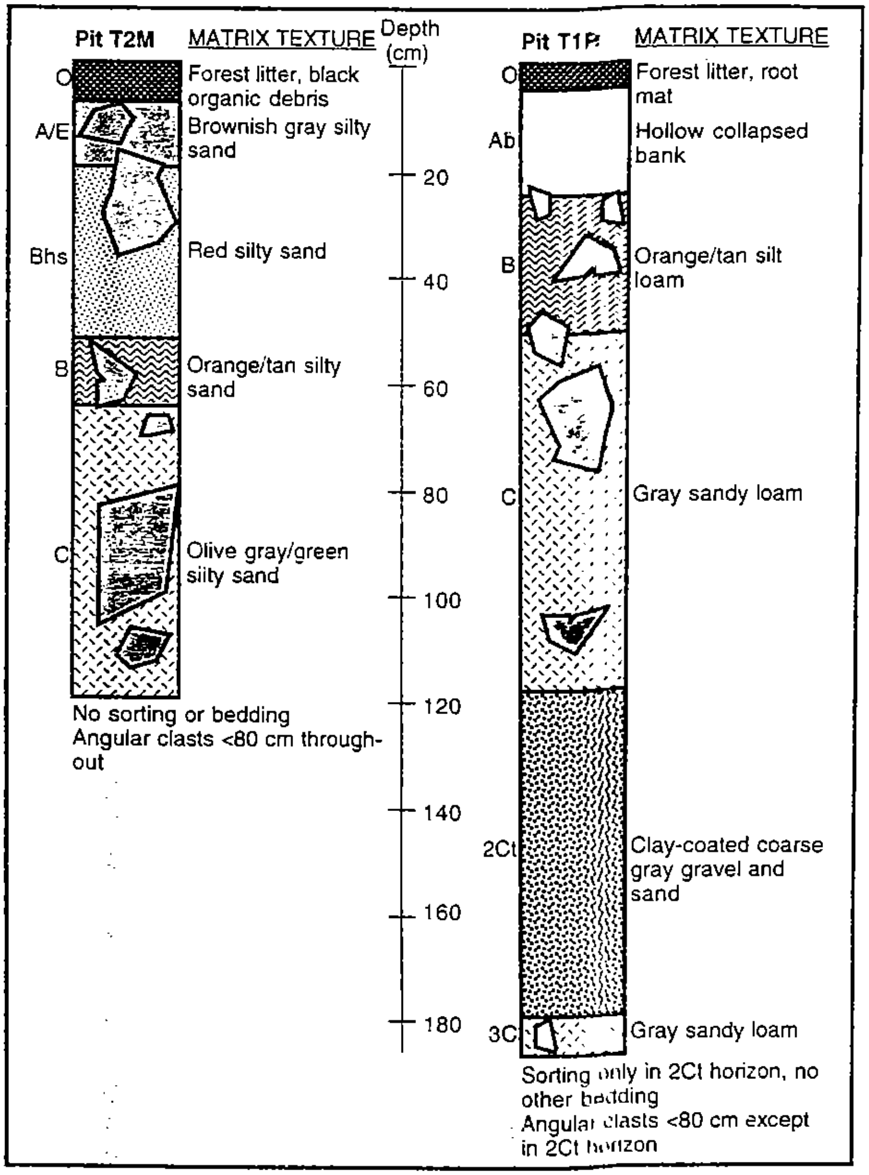

Figure 3. Soil profile for two pits (T2M and T1R) excavated on the moraine-like feature. Horizon texture and color for the soil matrix only is described. Angular clasts are indicated schematically by irregular polygons. Pit T2M, dug along the crest of the ridge, exposes unsorted, unbedded, angular boulders, cobbles, and pebbles in a silty sand matrix. Pit T1R, dug along the margin of the ridge where the ridge extends into the middle of the valley, exposes a more complex stratigraphy. Here unsorted, unbedded, angular clasts in a sandy or silty matrix overlie a layer of sorted gravel and sand.

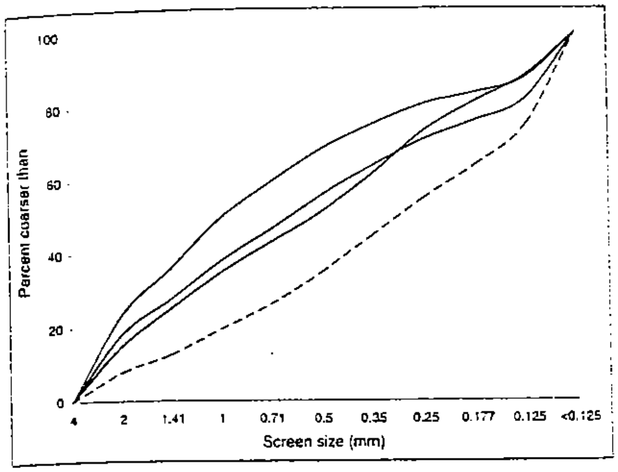

Figure 4. Grain size distribution of soil matrix gathered from unweathered parent materials at four sites – the three solid lines represent pits T2H, T2M, and T2R; the dashed line represents a sample of compact lodgement till exposed in a stream bank adjacent to the moraine-like feature. The graph plots the cumulative percentage of sediments coarser than screen size (mm) for each sample. Values shown are based on percentages of total sample weight after removal of clasts larger than 2 mm.

higher and lower elevation pits in this area, however, suggests that these sorted and unsorted materials were deposited contemporaneously, a situation common at glacial margins. Because abundant meltwater can sort and stratify morainal material, Goldthwait (1971) describes diamict with as much as 50% sorted material as "till" — a condition satisfied even in this exceptional pit.

The sediments we found within the ridge closely resemble diamicts interpreted as till in other areas of Vermont (e.g. Stewart and MacClintock 1971). Dreimanis (1976) found that ablation till generally contained >75% sand, and three soil pits on the Miller Brook moraine contained 64-73% sand. These tills were much coarser than the sample we analyzed from a nearby deposit of icesheet basal till (<45% sand), as would be expected in a local comparison of basal and ablation tills (Goldthwait 1971). However, ablation till can be deposited by either an alpine glacier or an icesheet. At some locations in Vermont, Stewart and MacClintock (1971) found that the stagnating icesheet formed "frontal" (terminal) moraines with matrix textures indistinguishable from those of alpine glaciers. Overall, the texture of the diamict is consistent with its interpretation as ablation till.

Morphology

Till is not a landform (Goldthwait 1971). An end moraine is a specific landform composed of till, typically forming "a convex down-valley arc…moored to the valley sides by lateral moraines" (Waitt and Davis 1988). Our map (Fig. 2) confirms that the current morphology of the ridge is consistent with that description except for the lack of a matching north-side lateral moraine. It is conceivable that a moraine on the north side of the valley was i) removed or obscured by downslope movement of colluvium, ii) eroded and/or covered by a small stream that is currently depositing an alluvial fan at the base of the slope, iii) eroded by Miller Brook, or iv) never deposited. In any case, the lateral extent, morphology, and elevation of the ridge allow us to test Wagner's (1970) original hypothesis that the ridge is a moraine. Specifically, we address the question of whether the ridge is a constructional or erosional landform and the various processes that might be responsible for its present form.

Table 1. Number and percentage of erratic clasts collected from soil pits at four locations on the moraine-like feature. The percentage of erratic clasts is a minimum value: non-erratic clasts have lithologies consistent with bedrock outcrops in the valley, but some of these could have been glacially transported into the valley from similar outcrops elsewhere.

Pit	# Sampled	# Erratic	% Erratic
T1M	233	33	14%
T1H	132	18	14%
T2H	100	12	12%
T2M	9	1	11%
TOTAL	474	64	14 %

Three pieces of evidence suggest that Holocene fluvial erosion could not have carved the ridge out of initially low-relief basin fill. First, a prominent closed drainage basin, currently the site

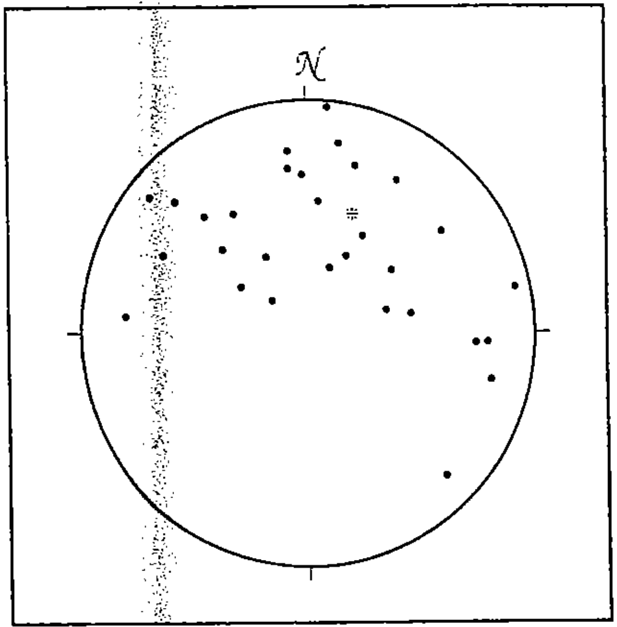

Figure 5. Lower hemisphere equal area projection of poles to flat pebbles taken from Pit T2H. The orientation of the ground surface where this pit was located is indicated by "". Planar clasts generally dip down slope, but are also oriented horizontally. Only one flat clast was observed to dip into the side of the ridge. All clasts were within 1 m of the ground surface.*

Table 2. Profile descriptions from ten soil pits on and near the moraine-like feature. Horizon depths are measured down from the ground surface to the top of the indicated horizon. Horizon texture and color for the soil matrix only is described, the presence of sorting, bedding, and matrix-supported clasts is noted.

T1H		T1M		T1R		T2H		T2M	
no sorting or bedding, angular clasts <10 cm		no sorting or bedding, angular clasts <50 cm		sorting only in 2Cl horizon, no other bedding Angular clasts <80 cm except in 2cl horizon		no sorting or bedding, subangular clasts <100 cm		no sorting or bedding angular clasts <80 cm	
Depth*	Matrix	Depth	Matrix	Depth	Matrix	Depth	Matrix	Depth	Matrix
0 Oa	black organic debris	0 Oe	root mat	0 Oe	root mat	0 Oe	root mat	0 Oa	black organic debris
8 E	dark gray silt loam	2 Oa	black organic debris	5 Ab	hollow collapsed bank	2 Oa	black organic debris	6 A/E	brownish gray silty sand
17 Bhs	reddish silt loam	11 A/E	dark gray sandy loam	25 B	orange/tan silt loam	16 A	dark brown/black sandy loam with leached pods	19 Bhs	red silty sand
39 B	tan sandy loam	20 Bhs	red sandy loam	52 C	gray sandy loam	43 E/A	chocolate brown/gray sandy loam	53 B	orange/tan silty sand
107 C	olive gray/green sandy loam	39 B	tannish oragne silty sand	117 2Ct	clay- coated coarse gray gravel and sand	54 Ob	blackish brown sandy loam	104 C	olive gray/green silty sand
		176 C	olive gray/green silty sand			56 Eb	grayish brown sandy loam		
						59 B	reddish orange silty sand		
						90 C	olive gray/green sand		

* depth from ground surface to top of this horizon

T2R		T3H		T3M		T3R		RTP	
no sorting or bedding, angular clasts <40 cm		no sorting or bedding, anugler clasts <1000 cm		no sorting or bedding, angular clasts <50 cm		Sorting and bedding below 34 cm Subrounded clasts in colluvium above 34 cm		no sorting or bedding, angular clasts <1000 cm	
Depth	Matrix	Depth	Matrix	Depth	Matrix	Depth	Matrix	Depth	Matrix
0 Oa	black organic debris	0 Oe	root mat	0 Oe	root mat	0 Oe	root mat	0 Oe	black silt loam
8 A	dark brown/black sandy loam	4 A	dark brown/black sandy loam in boulder matrix	5 A1	brown silty sand	2 A	chocolate brown silt loam	21 E	gray silt loam
11 E	gray sandy loam			22 A2	brown/black silty sand	34 Ob	black organics	27 Bhs	orange silt loam
18 Bhs	red silty sand			50 B	tan/orange silty sand	41 Eb	gray silt	45 C	dark brown/black sandy loam in boulder matrix
79 C	olivegray/green sand			81 C	olive green/gray sand	53 B1	red silt		
						79 B2	tan silt		
						105 B3	yellow/gray silt with oxidized sand layers		
						157 C1	coarse sand		
						159 C2	fine sand grading upwards to gray silty sand		
						182 C3	fine layered gray silt and very fine sand		
						200 C4	gravelly till		

of an ephemeral pond locally referred to as "the bog", occurs between the ridge and the mountainside ("B", Fig. 2). Fluvial erosion cannot have excavated this basin as there is no outlet. Second, peat sampled from 235 cm depth in this same bog was dated at 9280 years old +/-235 ^{14}C years, by Sperling et al (1989), indicating that this basin has been hydrologically closed for at least that long. Consequently, the ridge has been freestanding and separated from the mountainside for at least that long. Third, Pit T3R (Fig. 6), located at the foot of the ridge where it grades into a sloping pasture, reveals distinct layers of sorted silt and sand deposited directly on till. The till surface exposed in the bottom of the pit is sloping and projects upwards to the current slope of the ridge (at that location, strike 331° and dip 29° E). We interpret the fine sands and silts to be lacustrine in origin (lake surface elevation >342 m above sea level) deposited in a lake that existed during or immediately subsequent to ice retreat from the valley. These observations indicate that rather than being partially eroded since its deposition, the ridge has been partially buried in situ by organic material, alluvium, and shallow lake sediments.

Hooke (pers. comm.) suggested an alternate hypothesis, that the ridge might be a pro-talus rampart constructed from debris sliding over and accumulating at the base of perennial snow patches. The colluvium in pro-talus ramparts can closely resemble till, especially if they are fed entirely or in part by till deposited on steep upper slopes. Like tills, such deposits are composed of a coarse diamict and are described as "resembling small moraines, with which they may occasionally be confused" (Harris 1986). However, four traits of pro-talus ramparts are absent on the ridge. First, "even at depth fines form no more than a partial infill…not a matrix" (Ballantyne and Kirkbride 1986). Most large clasts in the Lake Mansfield ridge are entirely matrix supported. Second, clasts with flat faces should be oriented parallel to the parent hillslope and snowfield. Instead, the general orientation of 31 clasts with flat faces in Pit T2H was perpendicular to the parent hillslope and more closely parallel to the surface of the ridge

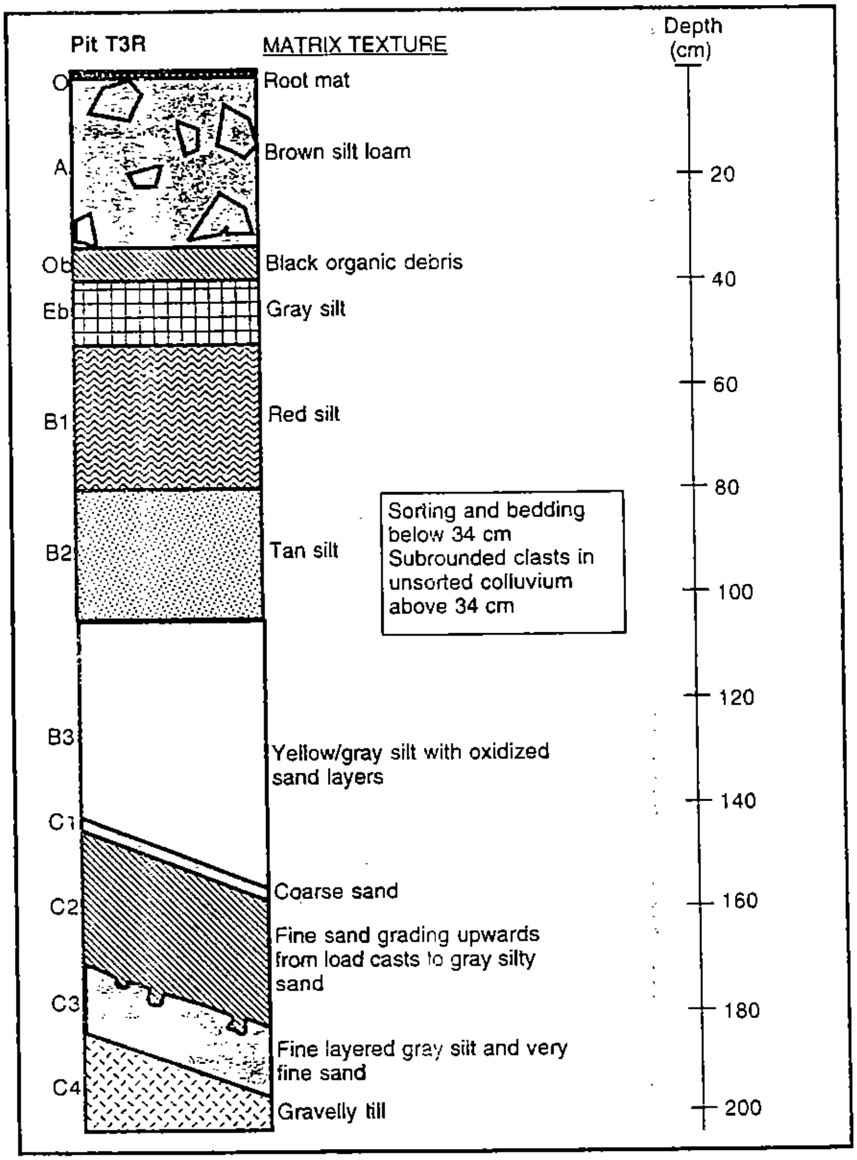

Figure 6. Soil profile for one soil pit (T3R) excavated adjacent to the moraine-like feature. Horizon texture and color for the soil matrix only is described. Angular clasts are indicated schematically by irregular polygons. The pit exposes well sorted and bedded silts and sands that we interpret as having been deposited in a lake. Lower layers are parallel to a dipping contact with coarse unsorted diamict at the bottom of the pit. This contact projects upwards to the exposed surface of the moraine-like feature, clearly indicating an onlapping relationship.

itself (Fig. 5). Third, ramparts contain very large clasts of predominantly or exclusively local origin (Ballantyne and Kirkbride 1986), while the ridge contained clasts of both local and erratic composition. Fourth, ramparts typically exhibit reversed grading, coarser particles on top and finer particles on the bottom, which is "distinctly different from the heterogeneous texture and mixed grading common to tills" (Fowler 1984). While our pits were excavated to only ~1 m depth, reversed grading was not observed. Only one of our ten pits fit any of these descriptions: pit T3H, the only site we examined which is located on the parent hillslope and currently exposed to rockfall. We examined photographs of protalus ramparts in other areas (Blagbrough and Breed 1967; Butler 1988) and found a substantial difference between the average clast size on pro-talus ramparts and on the ridge. Our data do not support the hypothesis that these ridges are pro-talus ramparts.

Although our sediment analysis could be further quantified by methods outlined in May and Dreimanis (1976), our data indicate that the Lake Mansfield ridge is largely composed of diamict that can be reasonably interpreted as till. Furthermore, the mapped outline of the Lake Mansfield ridge is consistent with its origin as a lateral and end moraine deposited at the margin of a glacier in the Miller Brook valley. Ongoing mapping by one of us (SFW) reveals a system of eskers 1 km down-valley from the area shown in figure 2, raising the alternative hypotheses that the Lake Mansfield ridge mapped

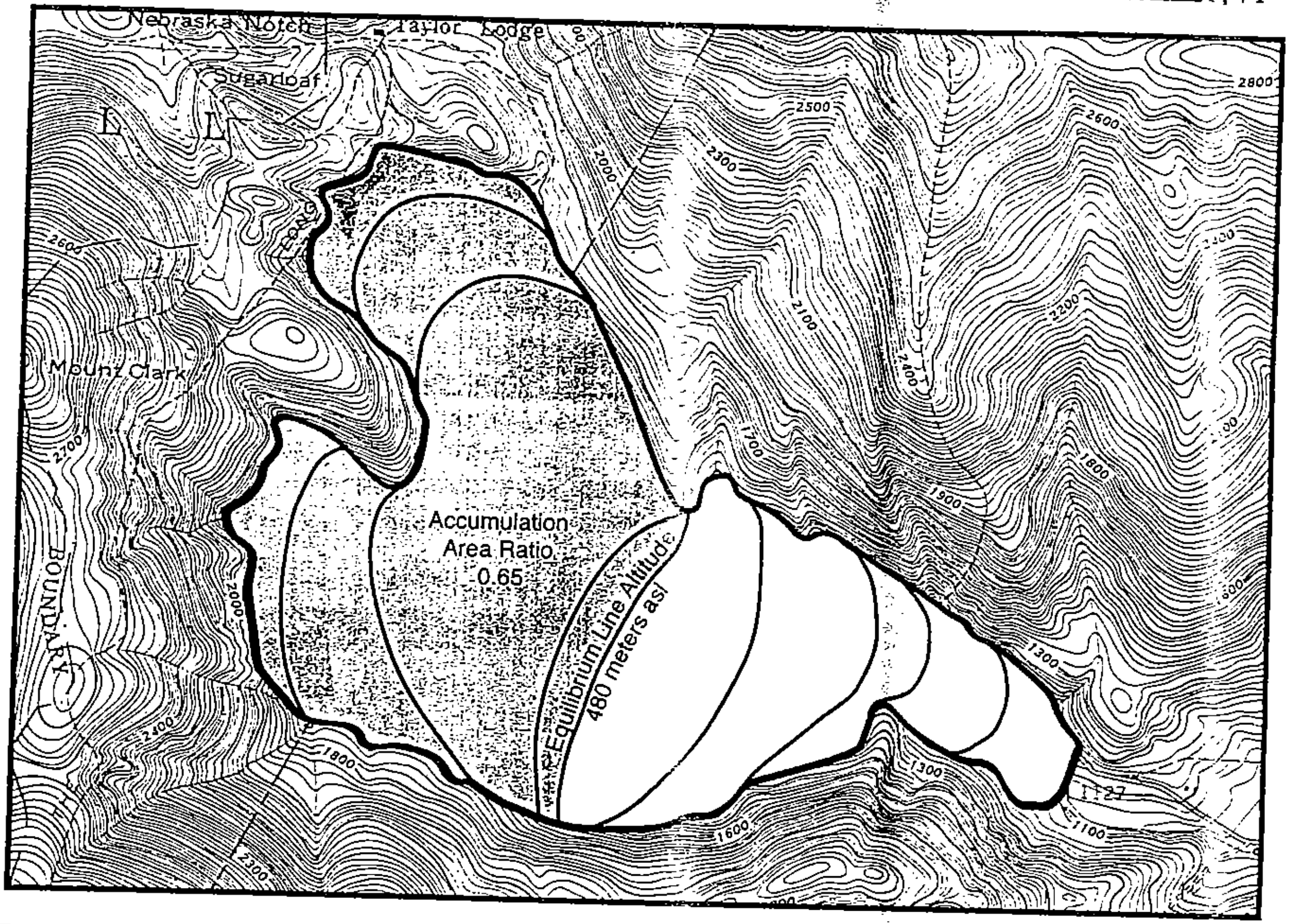

Figure 7. Reconstructed topography of a hypothetical alpine glacier in the Miller Brook valley, Lamoille County, north-central VT. The equilibrium-line altitude is based upon an accumulation area ratio of 0.65. The upper 65% of the glacier surface area is shaded. Base map from the United States Geological Survey Bolton Mountain quadrangle, VT.

here was formed as crack-fill in rotting, stagnant ice or perhaps is cored with fluvial material deposited in an esker and mantled with diamict. Our current data, however, suggests that the ridge is a moraine, composed of till and deposited by a glacier.

Genesis

What kind of ice formed the Miller Brook moraine? Wagner (1970) interpreted the moraine as a deposit left by an alpine glacier with its accumulation zone in the Miller Brook "cirque". Thirteen percent of counted clasts in the moraine were erratic, suggesting deposition by a continental icesheet. Bradley (1981) argued that the presence of erratic clasts "is not compelling evidence against short term post-Laurentide cirque activity; some time must be required for an alpine glacier to eradicate many meters of old till from a cirque". This point has been vigorously debated (particularly in New Hampshire's White Mountains, see summary in Fowler 1984), but it is clear that provenance studies are only rough indicators of glacial origin.

Our reconstruction of the climatic conditions necessary for formation of an alpine glacier may provide a more conclusive interpretation of the origin of the moraine. Figure 7 shows the reconstructed glacier in plan view. Based on an AAR of 0.65, the calculated equilibrium line lies on a hypothetical glacier surface at 480 m above sea level. This altitude is 2,568 m lower than the current July freezing isotherm, 3,048 m. Based on a lapse rate of 5.3°C/1,000 m, the summer temperature depression necessary for supporting an alpine glacier in the Miller Brook Valley is approximately 13.6°C. Pollen records in the nearby White Mountains have been interpreted by Spear (1989) to indicate a temperature depression immediately after ice retreat of only 5 to 10°C, 3.6 to 8.6°C warmer than our estimate of temperatures necessary to maintain an active alpine glacier in the valley.

Error may have been introduced into our estimates by inaccurate reconstruction of the cirque glacier topography, use of an inappropriate AAR or lapse rate, and invalid assumptions in our extrapolation of the JFI. The largest potential source of error in this analysis, however, is the assumption that modern snowfall accumulation rates are not significantly different than they were during the late-Pleistocene. Even in the unlikely event that total precipitation has remained constant, the proportion of total precipitation accumulating as winter snow would be altered by changes in temperature (Leonard 1989). Because the cumulative magnitude of these errors cannot be quantified, this analysis should be interpreted with caution. We believe it is a valid first approximation, however, because more detailed work in the Colorado Rockies has suggested that glaciation is much more responsive to temperature changes than changes in precipitation (Barry 1983; Leonard 1989). The discrepancy between our estimate of the summer temperature depression needed to support an alpine glacier and the temperature depression noted by Spear (1989) cannot be explained by small changes in winter accumulation rates.

Our ELA calculations suggest that a late-Pleistocene cirque glacier was unlikely. The formation of a push moraine by a minor readvance of an icesheet lobe has been observed and documented on the West Greenland icesheet (Ten Brink and Weidick 1974). In that instance, Ten Brink and Weidick concluded that a slight regional decrease in mean summer temperatures can, within several decades, cause an advance of the icesheet margin without an appreciable effect on the overall icesheet profile. The Laurentian icesheet could have flowed from the Champlain Valley over Nebraska Notch and into the Miller Brook valley during a period of general glacier retreat in the late-Pleistocene. This alternative hypothesis would explain the formation of a moraine in the Miller Brook valley by processes consistent with vegetative (Davis et al. 1980) and geomorphic (Goldthwait 1970; Waitt and Davis 1988) evidence of New England's late-Pleistocene climate. We suggest that the Miller Brook moraine was deposited by a lobe of the waning Laurentide icesheet, as proposed by Connally (1971) and Waitt and Davis (1988).

CONCLUSIONS

On the basis of our surveyed map, descriptions of soil profiles at ten locations, grain size analysis, pebble counts, and limited till fabric analysis, we support Wagner's (1970) assertion that the Miller Brook moraine-like feature is, in fact, a moraine. Furthermore, our evidence refutes alternative non-glacial theories of its formation. However, paleo-temperature estimates based on ELA reconstructions of a proposed cirque glacier in the valley are inconsistent with other studies of late-glacial paleo-climate. We support the hypothesis that the moraine was deposited by a lobe of the waning Laurentide icesheet, rather than by an independent mountain glacier.

ACKNOWLEDGMENTS

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REFERENCES

BALLANTYNE, C.K. and KIRKBRIDE, M.P., 1986, The characteristics and significance of some late glacial protalus ramparts in upland Britain: *Earth Surface Processes and Landforms*, v. 11, p. 659-671.

BARRY, R.G., 1983, Late-Pleistocene climatology, *in* Porter, S.C., (ed.), Late-Quaternary Environments of the United States, Volume 1, The Late-Pleistocene. University of Minnesota Press, Minneapolis, Minnesota, p. 390-407.

BLAGBROUGH, J.W. and BREED, W.J., 1967, Protalus ramparts on Navajo Mountain, southern Utah: *American Journal of Science*, v. 265, p. 759-772.

BRADLEY, D.C., 1981, Late Wisconsinan mountain glaciation in the northern Presidential Range, New Hampshire: *Arctic and Alpine Research*, v. 13, p. 319-327.

BUTLER, D.R., 1988, Neoglacial climatic inferences from rock glaciers and protalus ramparts, southern Lemhi Mountains, Idaho: *Physical Geography*, v. 9, p. 71-80.

CONNALLY, G.G., 1971, Pleistocene mountain glaciation, northern Vermont—discussion: *Geological Society of America Bulletin*, v. 82, p. 1763-1766.

DAVIS, M.B., SPEAR, R.W., and SHANE, L.C.K., 1980, Holocene climate of New England: *Quaternary Research*, v. 14, p. 240-250.

DENTON, G.H. and HUGHES, T.J., (eds.), 1981, The Last Great Ice Sheets. Wiley and Sons, New York, New York, 484 p.

DREIMANIS, A., 1976, Tills: their origin and properties. *In* Leggett, R.F., (ed.), Glacial Till—An Interdisciplinary Study. Royal Society of Canada, Ottawa, Canada, p. 11-49.

FEDERAL CLIMATE COMPLEX, 1995, International Station Meteorological Climate Summary (Computer File). Asheville, North Carolina.

FOWLER, B.K., 1984, Evidence for a late-Wisconsinan cirque glacier in King Ravine, northern Presidential Range, New Hampshire, U.S.A.: alternative interpretations: *Arctic and Alpine Research*, v. 16, p. 431-437.

GOLDTHWAIT, R.P., 1970, Mountain glaciers of the Presidential Range in New Hampshire: *Arctic and Alpine Research*, v. 2, p. 85-102.

GOLDTHWAIT, R.P., 1971, Introduction to till, today. *in* Goldthwait, R.P., (ed.), Till: A Symposium. Ohio State University Press, Columbus, Ohio, p. 3-26.

HARRIS, C., 1986, Some observations concerning the morphology and sedimentology of a protalus rampart, Okstindan, Norway: *Earth Surface Processes and Landforms*, v. 11, p. 673-676.

HAWKINS, F.F., 1985, Equilibrium-line altitudes and paleoenvironment in the Merchants Bay area, Baffin Island, N. W. T., Canada: *Journal of Glaciology*, v. 31, p. 205-213.

KRUGER, J., LILLYS, T., and MCLAUGHLIN, W., 1994, Alpine Glaciation in the Miller Brook Valley. Unpublished report, University of Vermont, 13 p.

LEONARD, E.M., 1984, Late Pleistocene equilibrium-line altitudes and modern snow accumulation patterns, San Juan Mountains, Colorado, USA: *Arctic and Alpine Research*, v. 16, p. 65-76.

LEONARD, E.M., 1989, Climatic change in the Colorado Rocky Mountains: estimates based on modern climate at late-Pleistocene equilibrium lines: *Arctic and Alpine Research*, v.

21, p. 245-255.

LEOPOLD, L.B., 1951, Pleistocene climate in New Mexico: *American Journal of Science*, v. 249, p. 152-168.

MAY, R.W. and DREIMANIS, A., 1976, Compositional variability in tills. *In* Leggett, R.F. (ed.), Glacial Till—An Interdisciplinary Study. Royal Society of Canada, Ottawa, Canada, p. 99-120.

MEIER, M.F. and POST, A.S., 1962, Recent variations in mass net budgets in western North America: *IUGG/IASH Committee on Snow and Ice, General Assembly, Obergurl, International Association of Science and Hydrology*, v. 58, p. 63-77.

MEIERDING, T.C., 1982, Late Pleistocene glacial equilibrium-line altitudes in the Colorado Front Range: a comparison of methods: *Quaternary Research*, v. 18, p. 289-310.

OHMURA, A., KASSER, P., and FUNK, M., 1992, Climate at the equilibrium line of glaciers: *Journal of Glaciology*, v. 38, p. 397-411.

PORTER, S.C., 1968, Determination of equilibrium-line altitudes for late-Quaternary alpine glaciers: *Geological Society of America Abstracts with Program*, p. 242.

PORTER, S.C., 1970, Quaternary glacial record in Swat Kohistan, West Pakistan: *Geological Society of America Bulletin*, v. 81, p. 1421-1446.

PORTER, S.C., 1975, Equilibrium-line altitudes of late Quaternary glaciers in the Southern Alps, New Zealand: *Quaternary Research*, v. 5, p. 27-47.

RICHMOND, G.M., 1965, Glaciation of the southern Rocky Mountains. *In* Wright, H.E. Jr. and Frey, D.G., (eds.), The Quaternary of the United States. Princeton University Press, Princeton, New Jersey, p. 217-230.

SPEAR, R.W., 1989, Late-Quaternary history of high-elevation vegetation in the White Mountains of New Hampshire: *Ecological Monographs*, v. 59, p. 125-151.

SPERLING, J.A., WEHRLE, M.E., and NEWMAN, W.S., 1989, Mountain glaciation at Ritterbush Pond and Miller Brook, northern Vermont, reexamined: *Northeastern Geology*, v. 11, p. 106-111.

STEWART, D.P., 1971, Pleistocene mountain glaciation, northern Vermont—discussion: *Geological Society of America Bulletin*, v. 82, p. 1759-1760.

STEWART, D.P. and MACCLINTOCK, P., 1971, Ablation till in northeastern Vermont. *In* Goldthwait, R.P. (ed.), Till: A Symposium. Ohio State University Press, Columbus, Ohio, p. 106-116.

TEN BRINK, N.W. and WEIDICK, A., 1974, Greenland icesheet history since the last glaciation: *Quaternary Research*, v. 4, p. 429-440.

UNITED STATES GEOLOGICAL SURVEY, 1976, Bolton Mountain Quadrangle, Vermont. Scale 1:24,000.

WAGNER, W.P., 1970, Pleistocene mountain glaciation, northern Vermont: *Geological Society of America Bulletin*, v. 81, p. 2465-2470.

WAITT, R.B. and DAVIS, P.T., 1988, No evidence for post-icesheet cirque glaciation in New England: *American Journal of Science*, v. 288, p. 495-533.

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