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Late Wisconsinan ice sheet flow across northern and central Vermont, USA

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A B S T R A C T

A compilation of over 2000 glacial striation azimuths across northern and central Vermont, northeastern USA, provides the basis for interpreting a sequence of ice flow directions across this area. The oldest striations indicate widespread ice flow to the southeast, obliquely across the mountains. Similarly oriented striations between northern Vermont and the ice sheet's terminus in the Gulf of Maine suggest that a broad area of southeast ice flow existed at the Last Glacial Maximum. Younger striations with more southerly azimuths on both the mountain ridgelines and within adjacent valleys indicate that ice sheet flow trajectories in most areas rotated from southeast to south, parallel to the North–South alignment of the mountains, as the ice sheet thinned. This transition in ice flow direction was time transgressive from south to north with the Green Mountains eventually separating a thick south-flowing lobe of ice in the Champlain Valley from a much thinner lobe of south-flowing ice east of the mountains. While this transition was taking place yet ice was still thick enough to flow across the mountains, ice flow along a narrow ~65 km long section of the Green Mountains shifted to the southwest such that ice was flowing into the Champlain Valley. The most likely process driving this change was a limited period of fast ice flow in the Champlain Valley, a short-lived ice streaming event, that drew down the ice surface in the valley. The advancing ice front during this period of fast ice flow may be responsible for the Luzerne Readvance south of Glens Falls, New York. Valley-parallel striations across the area indicate strong topographic control on ice flow as the ice sheet thinned.

1. Introduction

The Laurentide Ice Sheet first advanced across New England approximately 35–45 kyr BP and reached its maximum extent 23–28 kyr BP (Lamothe et al., 2013; Ridge et al., 2012). The earliest surficial geologic map of Vermont (Hitchcock et al., 1861) shows many glacial striae which Hitchcock (1878) combined with observations from across North America to show the Laurentide Ice Sheet's extent and “course of motion.” Since this early work and Goldthwait's compilation of glacial striations and erratic dispersal fans across New York and New England (in Antevs, 1922), geologists have recognized that ice flow across New England during the late Wisconsinan was generally towards the southeast and south.

Glacial striations, in conjunction with other glacial lineations, have been used in numerous studies to assess both small- and large-scale patterns of ice flow (e.g. Lamarche, 1971). While glacial striations have been measured as part of many mapping projects in Vermont, regional compilations of striation data are limited to Goldthwait (Figs. 5–3 in Flint, 1957), those occurring on the Surficial Geologic Map of Vermont (Stewart and MacClintock, 1970), Ackerly and Larsen (1987), and Wright (2006). The purpose of this paper is to use a large data set of accurately measured and located glacial striations across northern and central Vermont to reassess our understanding of changing Laurentide Ice Sheet flow directions across this area and to propose a model that explains why flow directions changed during deglaciation (Fig. 1).

2. Background and previous work

The timing of ice sheet retreat across New England is based on correlated and dated sections of glacial lake sediments, the North American Varve Chronology (Ridge et al., 2012). Based on that chronology, the ice sheet was retreating up the Connecticut river valley, past the southeastern corner of Vermont, approximately 15.5 kyr B.P. and was approaching the Québec border by ~13.4 kyr B.P., deglaciating Vermont over a span of ~2100 years

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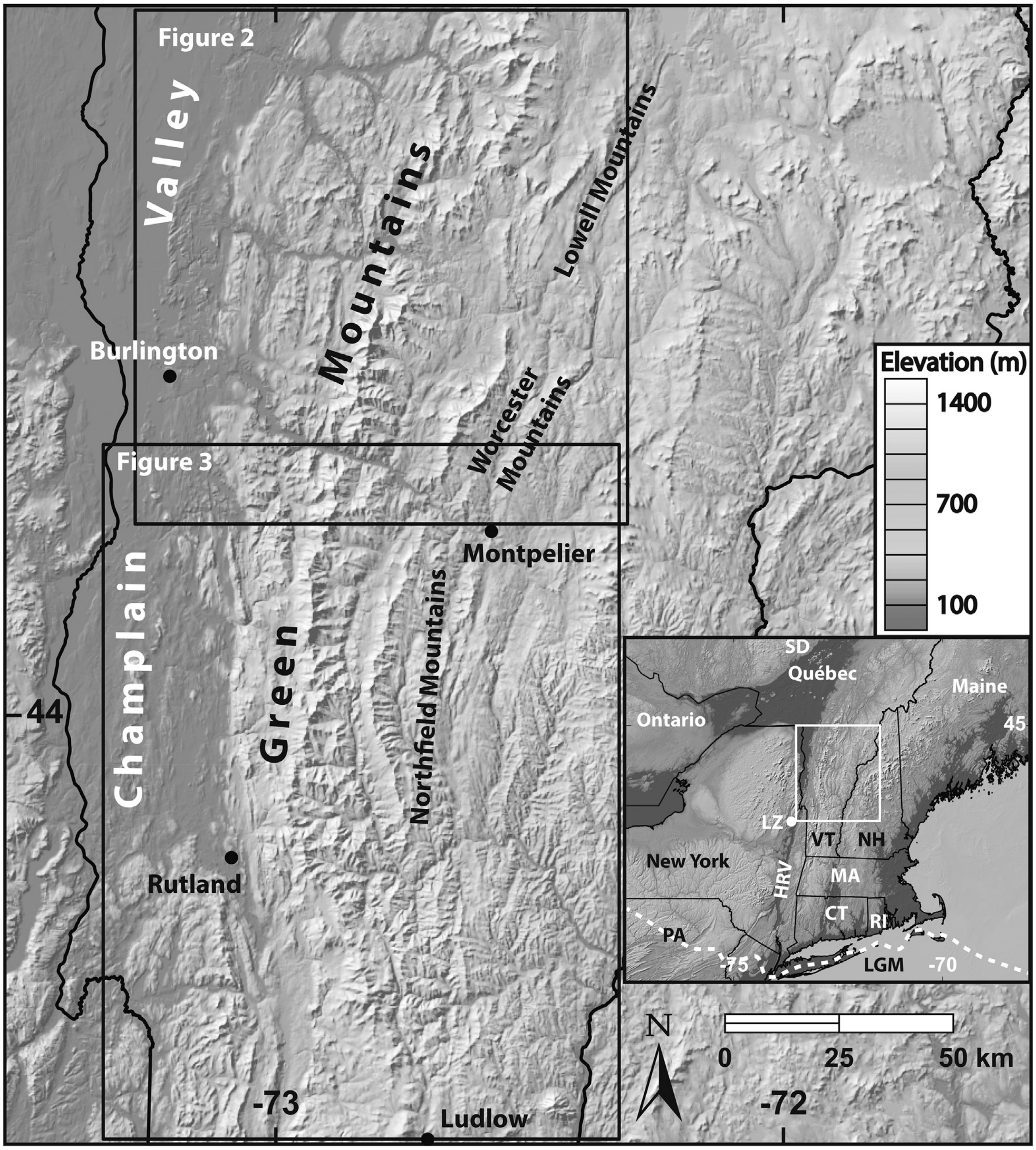

Fig. 1. Map of central and northern Vermont showing the extent of the field area and some of Vermont's major physiographic features. Elevation ranges between ~30 m in the Champlain Valley and over 1300 m for the highest peaks in the Green Mountains. Boxes outline extent of maps in Figs. 2 and 3. SD: St. Didace pluton, HRV: Hudson River Valley, VT: Vermont, NH: New Hampshire, PA: Pennsylvania, MA: Massachusetts, CT: Connecticut, RI: Rhode Island; White dot shows location of Luzerne Readvance (LZ), Dashed line shows approximate position of Last Glacial Maximum terminus (LGM).

(Ridge et al., 2012). However, by their nature the varve record is restricted to the valleys once occupied by glacial lakes and cannot be used to directly date deglaciation of the adjacent mountains.

While the first geologic map of Vermont showed a few glacial striations (Hitchcock et al., 1861), most early work on the state's glacial geology focused on the evolution of glacial lakes and subsequent down-cutting of stream channels through those lake sediments (e.g. Chapman, 1937; Merwin, 1908). The first comprehensive surficial mapping program in the state was systematically undertaken during the 1960's and compiled to produce the Vermont State Surficial Geology Map (Stewart and MacClintock, 1970). Stewart (1961) and Stewart and MacClintock (1969) summarized the results of this extensive mapping effort and put forth their interpretations of Vermont's glacial history. Based largely on till fabric measurements and several stratigraphic sections displaying what they interpreted to be multiple tills, they postulated the existence of three separate Wisconsinan till sheets deposited by ice flowing first from northwest to southeast (depositing the Bennington Drift Sheet), second from northeast to southwest (depositing the Shelburne Drift Sheet), and finally by ice flowing again from northwest to southeast (depositing the Burlington Drift Sheet). The aerial distribution of these till sheets and interpreted ice flow directions was illustrated in an inset map that accompanied the Vermont State Surficial Geology Map (Stewart and MacClintock, 1970).

Using erratic dispersal fans emanating southeast and south from

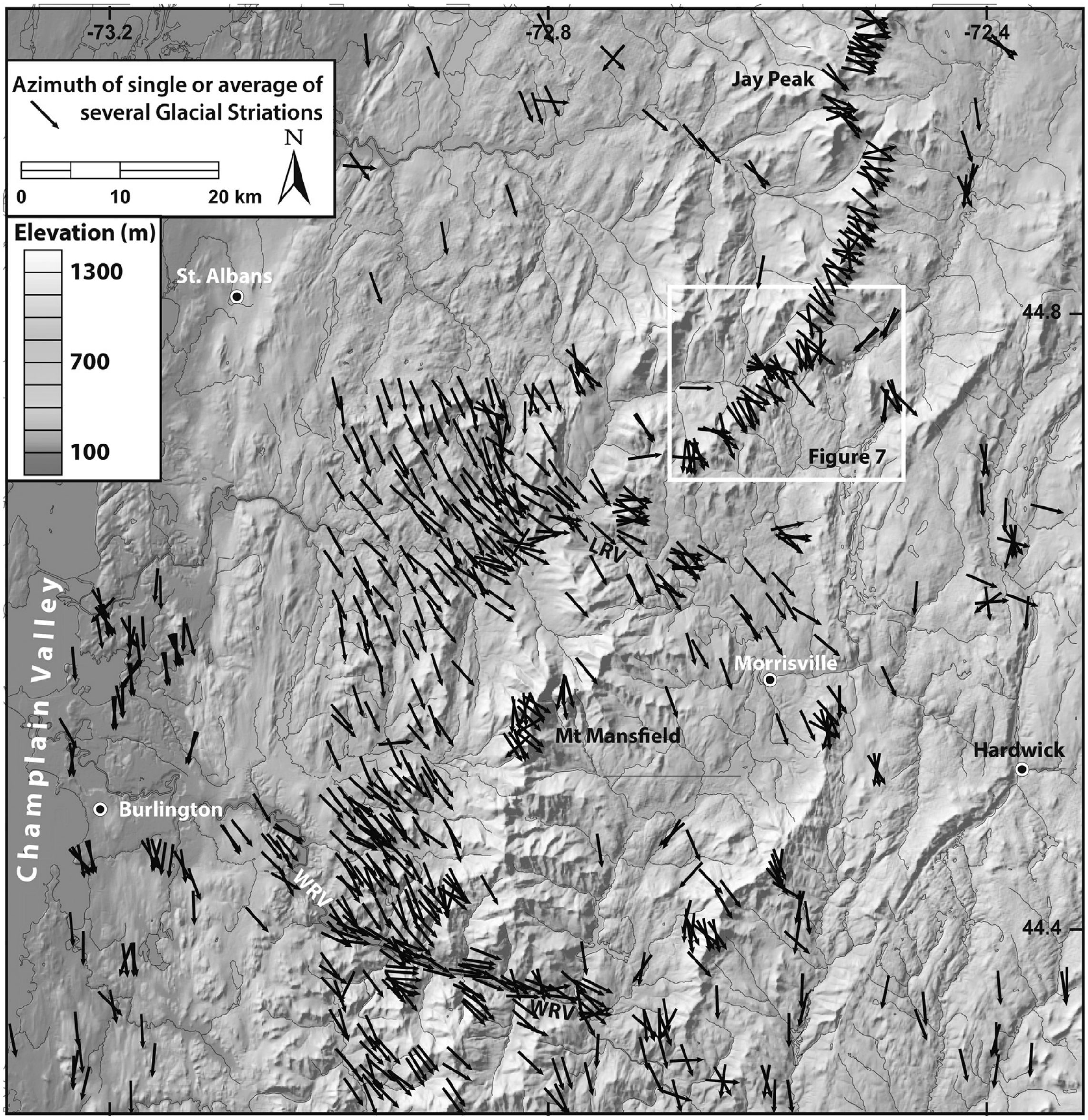

Fig. 2. Shaded relief map of glacial striations across northern Vermont. Where closely spaced, striations with similar azimuths have been omitted for clarity. High elevation striations in conjunction with asymmetric landforms and erratic dispersal indicate regional ice flow from northwest to southeast obliquely across the mountains. Most lower elevation striations are aligned parallel to the valleys they occur in. LRV: Lamoille River Valley, WRV: Winooski River Valley.

intrusive granite stocks in central Vermont, Larsen (1972) concluded that the Laurentide Ice Sheet had only flowed towards the southeast and south during the late Wisconsinan. Larsen et al., 2003 was also able to successfully trace a train of distinctive gneissic erratics from central Vermont in a NNW direction to their source, the St. Didace pluton in the Laurentian Mountains of Québec (Fig. 1). Larsen (1972) found no evidence in the erratic dispersion data to support Stewart and MacClintock's (1970) assertion that an ice sheet had flowed towards the southwest across most of Vermont. In a similar study of erratic dispersion, Munroe et al. (2007) found that K-feldspar from Devonian intrusions in central and northeastern Vermont had been transported south and southeast from these intrusions, but not to the southwest.

Wagner et al. (1972) cast further doubt on Stewart and MacClintock (1970) ice sheet flow history by remeasuring till fabrics at one of Stewart and MacClintock's key multiple till sites in the Champlain Valley and found no statistical distinction between the fabric of the upper and lower tills. Furthermore, detailed studies of the clay mineralogy in the tills and chemical alteration along joints in the lower till indicated that the upper till is in fact just a weathered portion of a single till sheet (Wagner et al., 1972).

3. Methods and study area

The work presented here compiles the azimuths of glacial striations and grooves across a large part of north–central Vermont. Whereas striations and grooves usually parallel one another on individual outcrops and striations are more common, only striations are referred to in the rest of this paper. This area straddles the Green Mountains from the Québec border southward to the latitude of Ludlow, Vermont and includes many parts of the Northfield-Worcester-Lowell mountain range to the east and much of the Champlain Valley to the west (Fig. 1). These striation data are sourced from: (1) unpublished, open-file 1:62,000 surficial geologic maps completed during a state-wide mapping program between 1956 and 1970 (Calkin, 1964; Calkin and MacClintock, 1965;

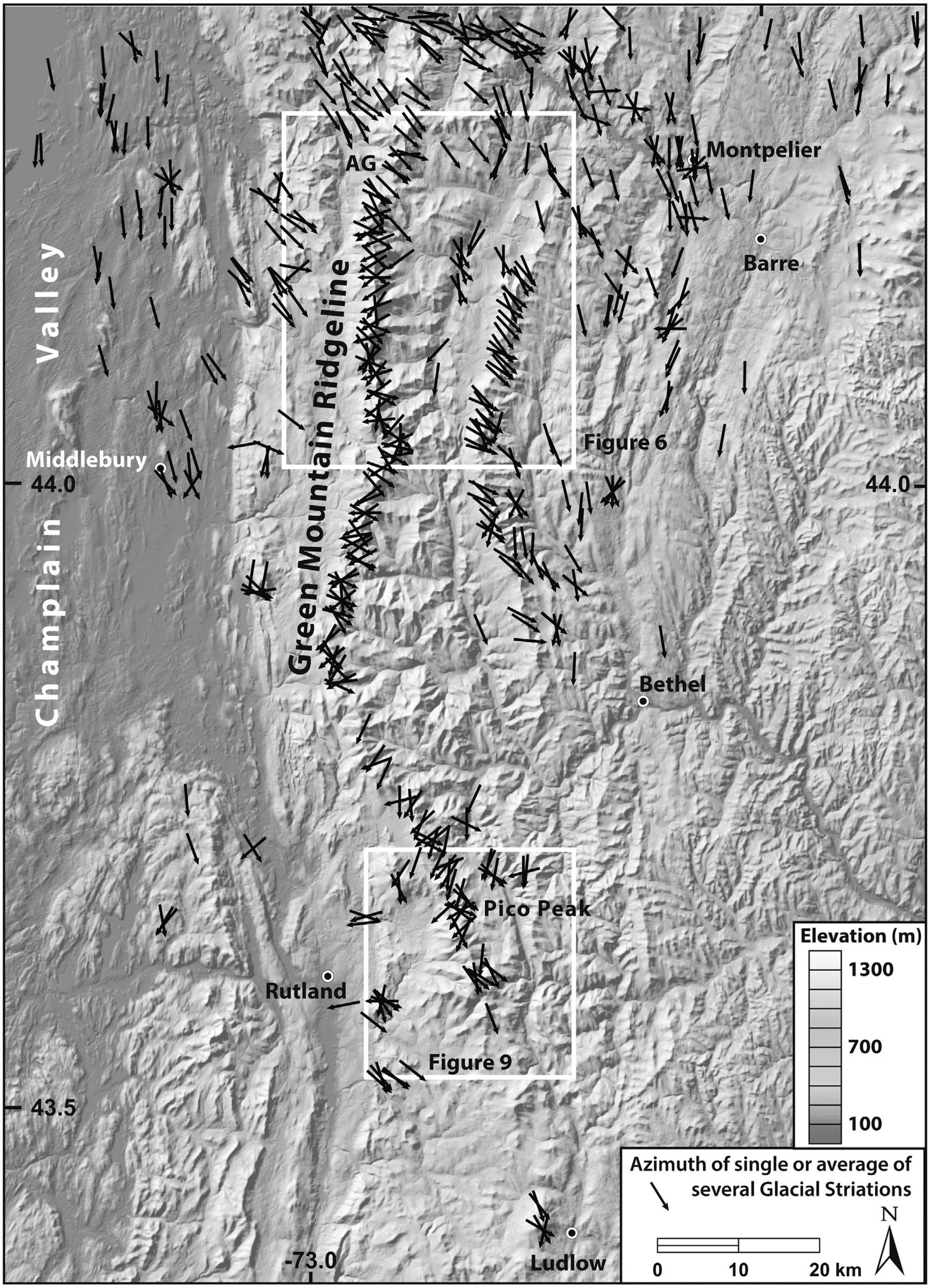

Fig. 3. Shaded relief map of glacial striations across central Vermont. In addition to the regional northwest–southeast striation set and striations aligned parallel to the major valleys, a distinct set of striations oriented northeast–southwest occurs along a ~65 km portion of the Green Mountain ridgeline between Appalachian Gap (AG) and Pico Peak. Boxes outline locations of more detailed maps.

Cannon, 1964; Christman, 1959; Christman and Secor, 1961; MacClintock, 1962, 1963a, b; 1966; Stewart and MacClintock, 1970), (2) more detailed 1:24,000 surficial maps of quadrangles, towns, and watersheds completed in the last 15 years (Brennan, 2005; Donahue et al., 2004; Dunn et al., 2007a, b; Larsen, 1999, 2012; Springston, 2011; Springston and DeSimone, 2007;

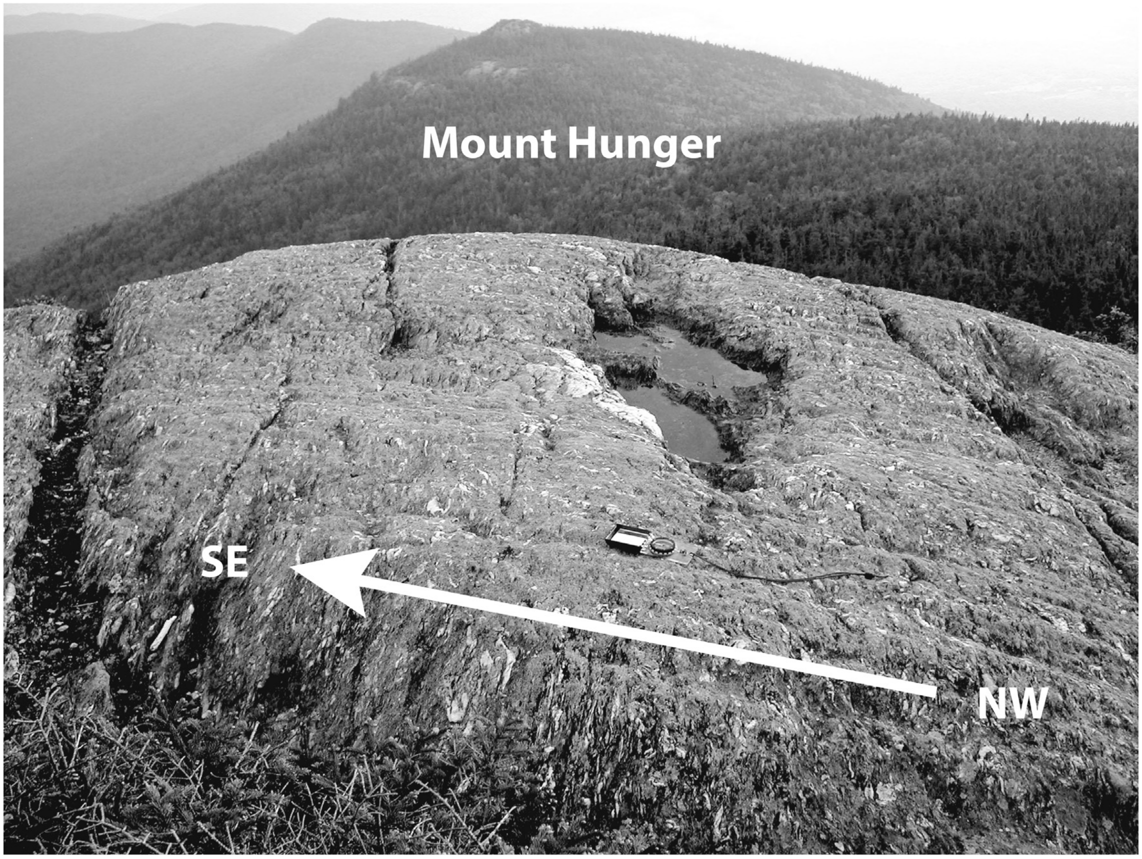

Fig. 4. View SSW along the ridgeline of the Worcester Range from the top of Mount Hunger (Elev. 1070 m asl). Weathered glacial grooves (parallel to compass) cut obliquely northwest–southeast across the mountains.

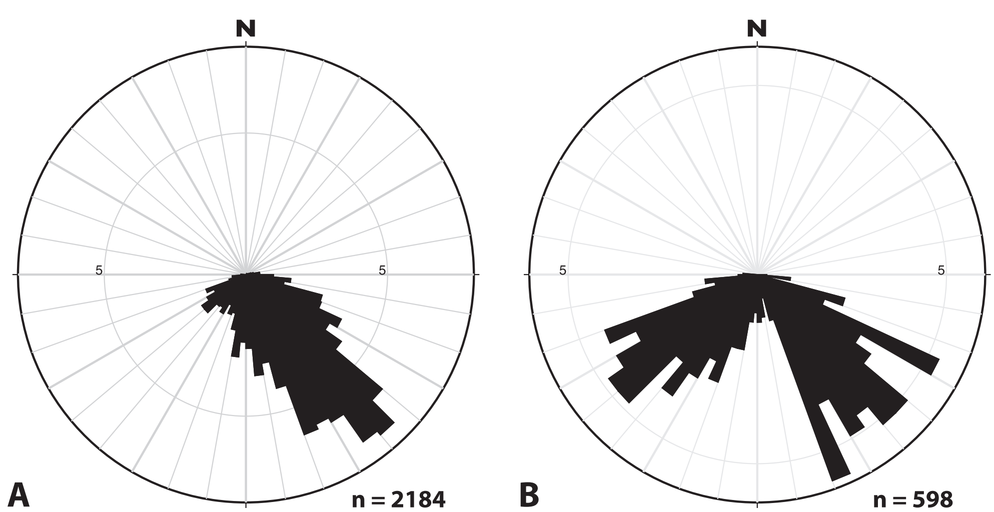

Fig. 5. Rose diagram plots of down-glacier striation azimuths. Data are subdivided into 5° increments. Radial scale is percentage of all striations plotted. (A) Plot of all 2184 striations recorded in the field area. The strong southeast maxima overwhelms lesser numbers of striations with southerly and southwesterly azimuths. (B) Plot of all 598 striation azimuths measured along and adjacent to the ridgeline of the Green Mountains south of the Winooski River valley (Fig. 3). The strongly bimodal distribution is clearly evident with 78% of all plotted striations aligned either southwest (39% between 200 and 250) or southeast (39% between 115 and 160).

Springston and Dunn, 2006; Springston and Kim, 2008, 2013; Springston and Maynard, 2010; Springston et al., 2004; Springston et al., 2014; Springston and Wright, 2009; VanHoesen, 2009; Wright, 1999, 2001, 2006, 2012; Wright et al., 2009a, 2010, 2009b) and Clark (unpublished maps, Norwich University), and (3) striation measurements by the author, largely along and adjacent to the ridgeline of the Green Mountains. The location and azimuth of striations plotted on older maps were digitized by hand. Field locations from more recent work were recorded using a hand-held GPS meter. These data are available as a supplemental data file.

Glacial striations compiled for this study are presented in Figs. 2, 3, 6, 7 and 9. Where striations on an outcrop vary in azimuth by less

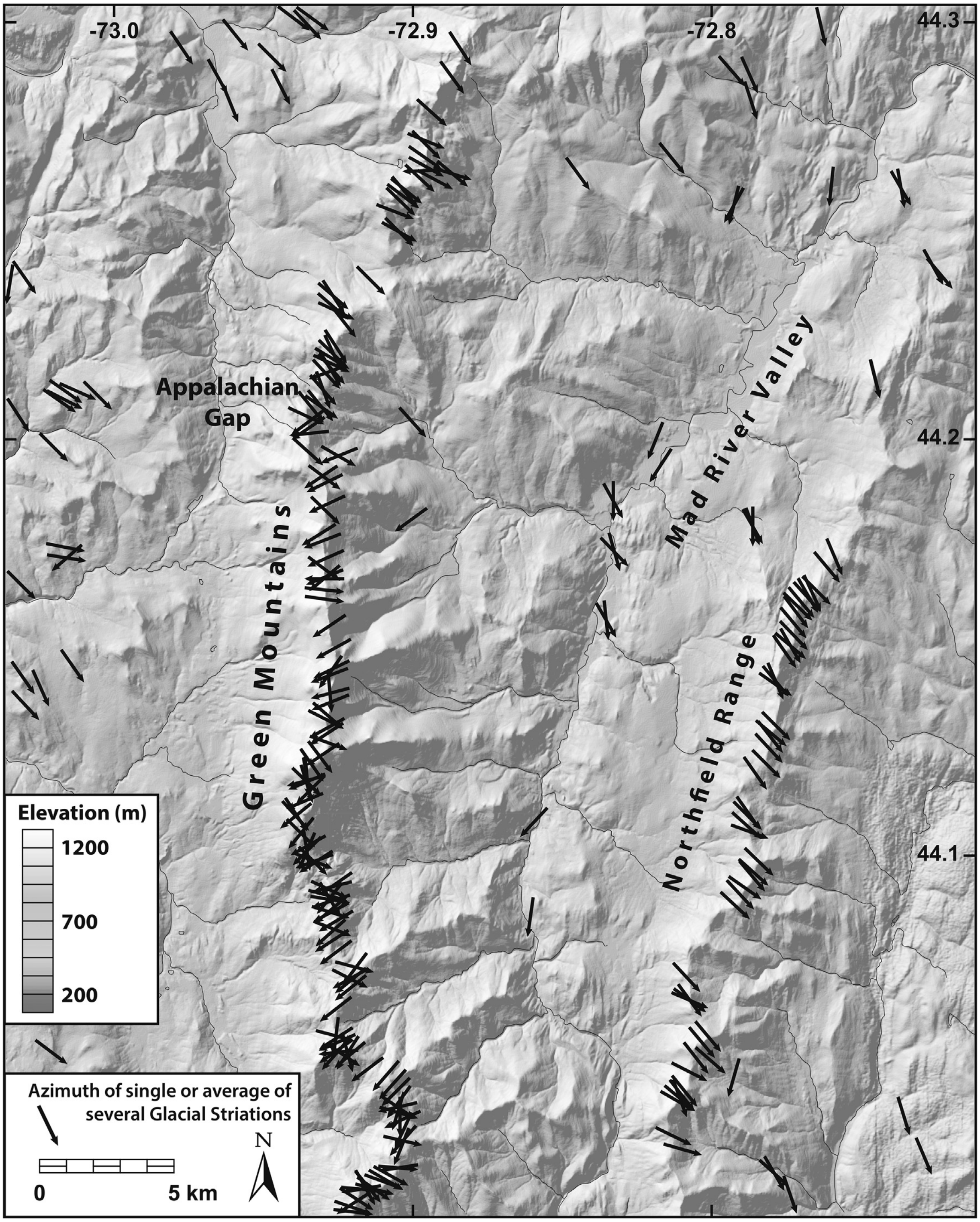

Fig. 6. Detailed shaded relief map of glacial striations in the mountains straddling the Mad River Valley (see Fig. 3 for location). Striations oriented northwest–southeast occur along both the Green Mountains and Northfield Range as well as the adjacent valleys. Striations oriented northeast–southwest are younger and restricted to areas on and adjacent to the Green Mountain ridgeline south of Appalachian Gap.

than 15° the average striation azimuth is plotted. When the range in striation azimuths exceeds 15° two arrows are plotted to indicate the end-member azimuths and to imply that these wider variations in azimuth may represent small shifts in ice flow direction. In some areas outcrops contain two or more striation sets that intersect one another at relatively high angles. It is possible to determine the relative age of these striation sets on some but not all outcrops. Where the relative ages of different striation sets are consistent across an area, those relative ages are assumed to hold at sites where it is not possible to determine the relative ages of striation sets based on field evidence. Every effort has been made to present as many striations as possible on these maps. However, in areas where closely spaced outcrops contain striations with similar azimuth, striations have been omitted for clarity without diminishing or biasing the interpretations.

Striation azimuths were collected over a 1300 m elevation range which has been utilized to provide further information about the relative ages of striations. Specifically, it is assumed that

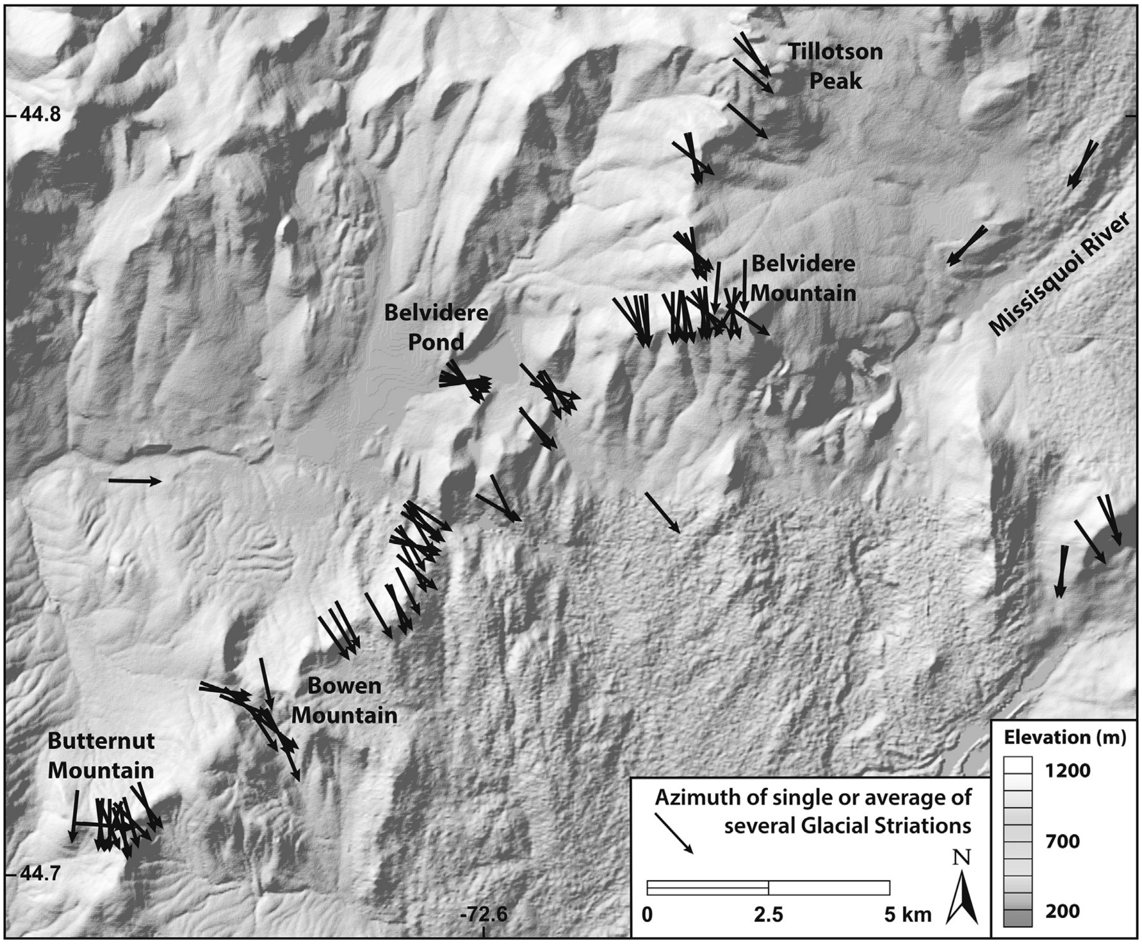

Fig. 7. Detailed shaded relief map of the northern Green Mountains (see Fig. 2 for location) showing the wide distribution of striations with northwest–southeast trends as well as areas with striations parallel to the valleys they occur in. Some areas preserve striations that range from the regional northwest–southeast trend to the trend of local topography (e.g. Belvidere Mountain, Belvidere Pond, Bowen Mountain).

striations occurring at the highest elevations, along the crest of the mountains, preserve the oldest directions of ice flow. These striations were not erased by ice flowing in other directions later in time. Striations occurring at progressively lower elevations may still preserve those older ice flow directions, but also record more recent ice sheet flow, which is absent at the highest elevations.

While the striations themselves provide no reliable sense of asymmetry with which to assess a unique ice flow direction (Iverson, 1991), the direction of ice flow can be consistently determined across the area by both small- and large-scale roches moutonneé, small-scale crag and tail structures (e.g. tails of less eroded rock down-glacier from quartz veins), and the distribution of distinctive erratics down-glacier from their sources. Consequently, on the maps that follow striations are shown as arrows even though it's not possible to determine a unique flow direction on most striated outcrop surfaces.

4. Striation data

Glacial striations are plotted on two maps that encompass the entire field area from the Québec border ~180 km south to Ludlow, Vermont (Figs. 2 and 3). More detailed maps depict striation patterns across more restricted areas. Among the 2184 striations collected for this study several distinct sets occur over all or restricted parts of the mapped area and are described below.

4.1. Regional Northwest–Southeast Striation set

Striations aligned generally northwest–southeast are widely distributed across the field area, are present at all elevations (30–1340 m), but are particularly well preserved along the high ridgelines of both the Green Mountains and lower elevation mountain ranges to the east (Figs. 2–4). These striations most commonly trend between 130° and 160° although striations occurring in the northernmost Green Mountains are oriented in a more easterly direction (Figs. 2 and 5A). This set of striations is generally parallel with southeast ice flow direction indicators down-glacier from Vermont in central New Hampshire and southern Maine (Thompson and Borns, 1985) as well as immediately north of the field area in southern Québec (Parent and Occhietti, 1999), (Fig. 1).

4.2. Restricted Northeast–Southwest Striation set

A second set of younger, cross-cutting striations occurs along an ~65 km segment of the Green Mountain ridgeline beginning 0.6 km north of Appalachian Gap and extending south to the north side of Pico Peak (Fig. 3). This striation set was first described by Ackerly and Larsen (1987). These striations are aligned generally northeast–southwest, almost perpendicular to the older northwest–southeast set (Fig. 5B), and are restricted to elevations between 650 and 1240 m. Striations in this set are also restricted in an east-west

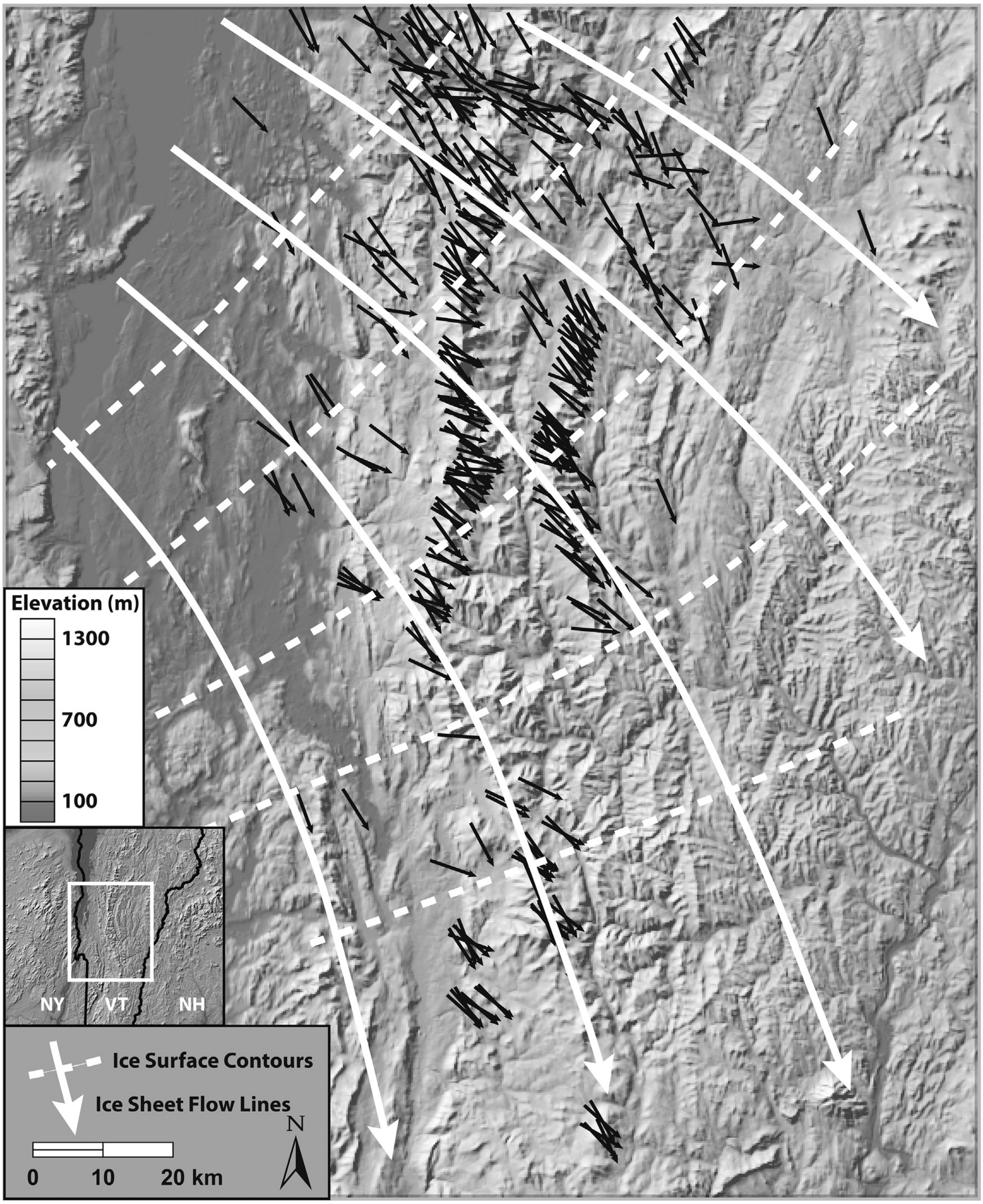

Fig. 8. Hypothetical curved ice sheet flow lines and associated ice surface contours across central Vermont show the transition from SE to SSE directed ice flow at a time when the ice sheet was still thick enough to flow over the mountains but was initially affected by the north–south trend of the underlying mountains and valleys. As the ice sheet thinned, this pattern of ice sheet flow lines migrated northwards. For clarity, only striations with southeast to south azimuths are shown.

direction to a narrow zone adjacent to the Green Mountain ridgeline (Figs. 3 and 6). Only a few northeast–southwest striations have been observed along the crest of the Northfield Range, despite that range lying only 10–20 km east of the Green Mountains and these few are aligned in more northerly directions (Figs. 3 and 6). Similarly, very few striations from this set have been observed more than ~5 km west of the ridgeline although this area has not been mapped in as much detail and more recent southward movement of the ice lobe in the Champlain Valley may have erased most older striations.

A much more restricted area with striations aligned northeast–southwest occurs immediately south of Mount Mansfield (Fig. 2). In this area striations with this orientation are very faint and their age relative to the dominant northwest–southeast set could not be determined.

4.3. Striations in notches and valleys

Striations occurring within valleys, ranging in size from small notches cutting across the mountains to major river valleys to the Champlain Valley, commonly contain striations recording ice flow

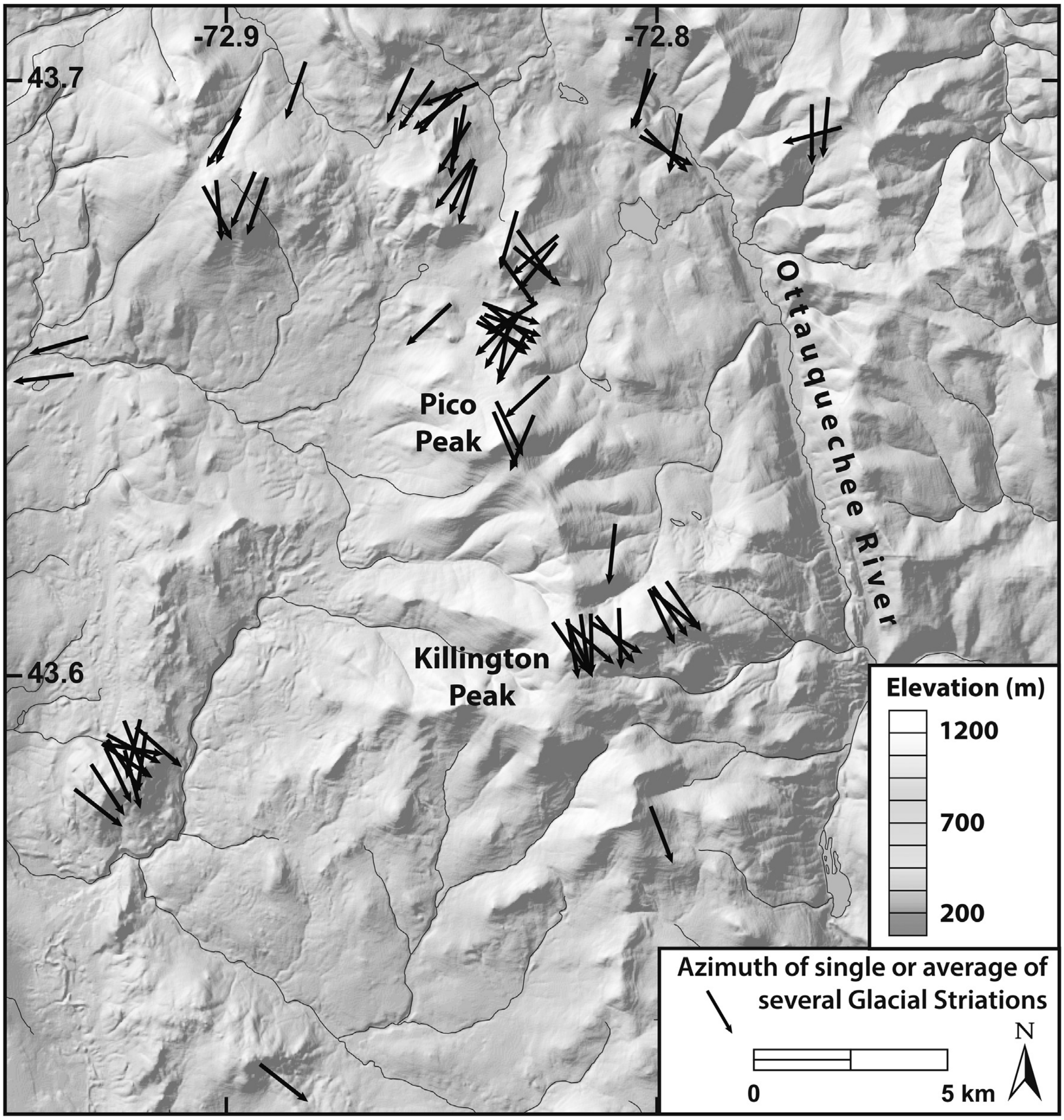

Fig. 9. Detailed shaded relief map shows the southern limit of southwest-directed striations occurring on Pico Peak (see Fig. 3 for location). Initiation of southwestern ice flow into the Champlain Valley began when the ice sheet immediately south of Pico Peak wasn't thick enough to flow across the mountains.

parallel to those valleys (Figs. 2 and 3). Cross-cutting relationships indicate that these valley-parallel striations are younger than the regionally pervasive northwest–southeast set. A striking pattern visible on Fig. 2 is the convergence of glacial striations occurring northwest of both the Lamoille and Winooski River valleys into parallelism with those valleys. On a more regional scale, striations occurring in the broad Champlain Valley and smaller north–south valleys within and east of the mountains generally trend north–south, parallel to the trend of those valleys (Figs. 2 and 3). In many areas single or closely spaced outcrops preserve striations that range from the regional northwest–southeast trend to trends parallel to local topography (Fig 7).

5. Discussion

5.1. Regional southeast ice flow

The oldest record of ice flow across the field area is the regionally extensive set of northwest–southeast glacial striations that are particularly prevalent across the high-elevation mountain ridgelines (Figs. 2, 3 and 6). This striation set maintains a relatively uniform azimuth across the field area (Ave. 136°, Fig. 5) and is parallel with striations measured across a wide swath of south-central New Hampshire and southern Maine, areas immediately down-glacier from northern and central Vermont (Goldthwait in Antevs, 1922; Thompson and Borns, 1985). If the ice sheet across New England was warm-based at the LGM, the consistent northwest–southeast azimuth of striations extending from northern and central Vermont down-glacier to the ice sheet's LGM terminus may indicate a broad area of southeast ice flow at the LGM. Hughes (1987), Kleman (1990), and others have recognized that the striations preserved on bedrock surfaces have generally formed in a time-transgressive manner, new directions of ice sheet motion relatively quickly erasing evidence of older ice flow directions. The excellent preservation of this striation set across high-elevation areas implies that the ice sheet never flowed in other directions

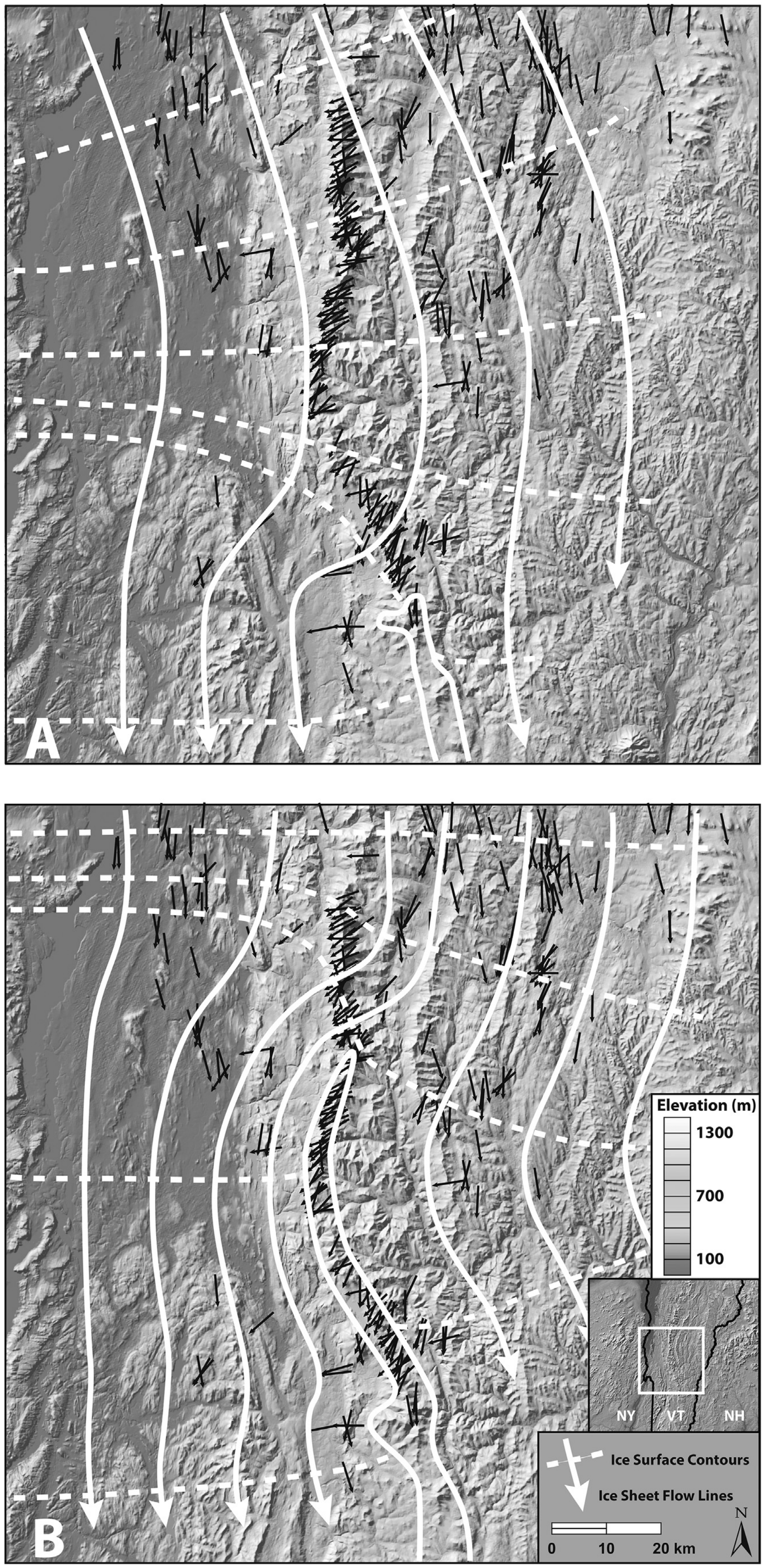

Fig. 10. Ice surface contours and flow lines reconstruct the hypothetical geometry of the ice sheet (A) shortly after the inception of southwestward ice flow into the Champlain Valley and (B) at a later period of time when the zone of southwestward ice flow across the Green Mountains migrated farther north. Areas of closely-spaced ice surface contours on both maps show the steepened ice surface separating rapidly flowing ice with a low slope to the south from more slowly flowing ice to the north. In this reconstruction southwest ice flow occurs along a restricted length of the Green Mountain ridgeline that migrates north with time. The Green Mountain ridgeline is shown (A) emerging from the ice and (B) expanding north as the ice surface in the Champlain Valley continues to lower. Ice flow in the northern part of map area is still to the SSE but transitions down-glacier to south and southwest (A). For clarity, only striations with southerly and southwesterly azimuths are shown. The explanation serves both maps.

long enough to erase these striations or that they are preserved because the ice sheet transitioned to cold-based conditions after they formed. It therefore seems likely that, as long as the ice sheet was thick enough to flow across topography, southeast-directed ice flow continued as the ice sheet retreated across New England. If the ice sheet across central New England was cold-based at the LGM, these widespread northwest–southeast striation trends similarly suggest ongoing southeast-directed ice flow as the margin of the ice sheet transitioned to warm-based conditions during its retreat across the area.

Across most of the high-elevation ridgelines the southeast-directed striation set includes striations ranging in azimuth from almost east-west to north–south. Where relative ages can be ascertained, striations with more southerly azimuths (SSE to S) cross-cut or appear sharper and are better preserved than those with more southeast to easterly azimuths. It therefore appears that ice flow across the mountains rotated from southeast to south as the ice sheet thinned across the mountains and was increasingly influenced by the many underlying north–south mountain ranges and intervening valleys. Fig. 8 depicts this change in ice flow at a snapshot in time using a hypothetical set of curved flow lines drawn parallel to the underlying striations. This directional shift was time-transgressive, progressing northward as the ice sheet thinned. That said, striations indicating south-directed ice flow are rare or absent along many parts of the Green Mountain ridgeline (Fig. 6) suggesting that the ridgeline was quickly emerging from the ice or frozen to its bed during the transition from southeastern to southern flow. Erratic dispersion fans across Vermont extend both southeast and south of the source rocks reflecting the summation of ice flow first to the southeast and then the south (Goldthwait in Antevs, 1922; Larsen, 1972; Larsen et al., 2003; Munroe et al., 2007).

5.2. Southwest ice flow into the Champlain Valley: evidence of ice streaming?

An aerially restricted set of younger striations, aligned northeast–southwest, occurs along a 65 km length of the Green Mountain ridgeline and marks a significant change in the geometry of the ice sheet (Fig. 3). To facilitate this substantial change in ice flow direction the ice surface slope must have changed from southeast to southwest to drive ice flow obliquely across the mountains and into the Champlain Valley. Specifically, the ice surface elevation east of the mountains must have risen or the ice surface elevation west of the mountains, in the Champlain Valley, must have fallen (Ackerly and Larsen, 1987). It's difficult to imagine a process that could thicken the ice sheet east of the mountains and not simultaneously thicken the ice sheet in the much deeper Champlain Valley, especially given that regional ice flow was, until this time, from the northwest. Furthermore, if the ice sheet east of the mountains did thicken from ice sourced from the north, southwest-directed ice flow would have occurred across the northern Green Mountains and progressed southward, but no evidence of southwest ice flow exists in the northern mountains.

On the other hand, the ice sheet in the Champlain Valley may have thinned in response to accelerated ablation or rapid ice flow. The relative timing of ice sheet retreat in the Champlain Valley versus areas east of the Green Mountains is constrained by ice-dammed lakes in valleys east of the mountains. Specifically, at the same time the ice sheet in the Champlain Valley was sufficiently thick to dam both the Winooski and Lamoille River Valleys forming Glacial Lake Winooski, the ice sheet east of the mountains was retreating north of these drainage basins (Larsen, 1972, 1987) (Fig. 2). While these river valleys lie north of the area of southwest-directed ice flow (Fig. 3), it seems likely that the margin of the thick ice lobe in the Champlain Valley was always farther south than the ice margin in the adjacent mountains making it unlikely that ablation alone could differentially thin the ice sheet in the Champlain Valley.

The initiation of rapid ice flow in the Champlain Valley, ice streaming or a glacial surge, may also have thinned the ice sheet in this area. The most recent compilation of paleo-ice streams within the Laurentide Ice Sheet shows no ice stream in the Champlain Valley (Margold et al., 2015, 2014). However, the area does contain several types of evidence used to identify paleo-ice streams (Margold et al., 2015; Stokes and Clark, 1999, 2001). The most common of these, streamlined bedforms with length:width ratios exceeding 10:1, are visible on Lidar hillshade maps in upland areas (e.g. Springston and Kim, 2015), although landforms on the till surface in much of the valley are masked by thick sequences of lacustrine and marine sediments. The Champlain Valley is also a substantial trough. While its origin is structural (a failed rift) and not glacial, its size is well within the dimensions of modern ice streams. Furthermore, most of the valley is underlain by Ordovician shales and limestones (Ratcliffe et al., 2011) which have sourced tills with high percentages of silt/clay and low shear strengths (Springston and Wright, 2009). Converging ice flow is another criteria for ice streaming and I propose here that the southwest-directed striations set described herein formed from converging flow into the Champlain Valley during a period of fast ice flow. Fast ice flow may occur during a glacial surge or ice streaming, processes occurring on time scales ranging, respectively, from years to millennia (Margold et al., 2015). The ~65 km length of Green Mountain ridgeline affected by southwest-directed ice flow is much longer than areas affected by glacial surges suggesting that this was a short-lived streaming event.

A detailed map of the area near Pico and Killington Peaks shows that striations with southwestern azimuths occur no farther south than Pico Peak (Fig. 9). A reasonable inference therefore, is that the ice sheet south of Pico Peak was not sufficiently thick to flow across the mountains when southwest ice flow initiated and was instead divided by the Green Mountain ridgeline into two independent south-flowing lobes south of this area. Two maps reconstruct the geometry of the ice sheet when (1) ice initially began flowing into the Champlain Valley (Fig. 10A) and (2) at a later point in time when the zone of southwest-flowing ice had migrated farther north (Fig. 10B). Hypothetical ice flow lines are drawn parallel to what are presumed to be coevally produced striations. In these reconstructions southwest ice flow is enabled by a zone of steeply sloping ice (closely-spaced contours on the maps) separating fast flowing ice to the south with a low surface slope from more slowly flowing ice with a steeper slope to the north (Fig. 10A). Northward propagation of the steepened ice surface would force the inflection in the ice surface contours to similarly migrate to the north shifting the zone of southwest-flowing ice northwards (Fig. 10B).

Outcrops with southwest-trending glacial striations end abruptly ~1 km south of Appalachian Gap and only one other striated outcrop, ~0.5 km north of Appalachian Gap, contains striations with southwestern azimuths (Fig. 6). Therefore, the inflection of the ice surface causing southwest-directed ice flow into the Champlain Valley, i.e. the boundary between fast-flowing ice to the south and more slowly moving ice to the north, did not progress any farther north than here. If it did, then later ice flow to the southeast erased any evidence of flow to the southwest north of Appalachian Gap. As noted earlier, a second very limited area of faint northeast–southwest striations exists immediately south of Mount Mansfield (Fig. 2) suggesting that the processes responsible for lowering the ice surface in the Champlain Valley occurred again when the ice sheet margin was farther north, albeit very briefly. The excellent preservation of southwest-directed striations south of Appalachian Gap and lack of overprinting by younger striations suggests that these mountains emerged from the ice shortly after southwest-directed ice flow ceased.

The limited extent of the northeast–southwest striation set (Fig. 3) indicates that the processes responsible for driving ice flow into the Chaplain Valley occurred for a restricted period of time. If the ice sheet thinned in response to fast ice flow, the ice margin must have advanced when fast ice flow initiated and then rapidly retreated and/or stagnated when fast ice flow ceased. Connally and Sirkin (1971) describe several sections in the upper Hudson River valley showing evidence of a glacial readvance which they called the Luzerne Readvance (Fig. 1). These sections lie ~90 km south of the southern limit of the southwest striation set and may have formed when ice advanced during the fast ice flow event proposed here. Additionally, an extensive area with kame and kettle topography lies 12–24 km northeast of the sections described by Connally and Sirken (1971) and may have formed when rapid ice flow stopped and large areas of thin ice stagnated.

5.3. Topographically controlled ice flow in valleys

In the many mountain valleys in the field area, the youngest striations usually parallel those valleys (Figs. 2, 3 and 7). The logical interpretation is that topography began influencing ice flow as the ice sheet thinned, a common observation along the margin of modern ice sheets. In most areas ice flow shifted from southeast to south as most of the valleys in the field area are aligned parallel to the north–south trend of the mountains (Fig. 8). Many small notches, however, cut across the mountains and striations within them indicate that they too controlled local ice flow (Fig. 7). On a larger scale, the Lamoille and Winooski river valleys both cut completely across the mountains and effectively funneled ice from the Champlain Valley across the mountains. On the west side of the mountains glacial striations converge into these valleys. The aerial extent of this convergence is an indication of the area of ice in the Champlain Valley that was contributing ice to these outlet glaciers (Fig. 2). As noted earlier, ice flowing in these valleys also dammed those drainages producing large glacial lakes east of the mountains (Fig. 2, Larsen, 1972, 1987).

6. Conclusions

The oldest record of ice flow across northern and central Vermont comes from a widespread set of glacial striations indicating region-wide ice flow from northwest to southeast. These striations are particularly common along the mountain ridgelines. Striations with similar azimuths occur southeast of the field area in New Hampshire and Maine. This suggests that regional southeast ice flow continued as the ice sheet retreated from coastal New England to Vermont as long as the ice sheet was thick enough to flow across the mountains.

As the ice sheet thinned across the mountains, ice flow became topographically controlled and in most areas rotated from southeast to south, parallel to the Champlain Valley and other north–south river valleys in the mountains. This process divided the ice sheet into at least two south-flowing lobes, one occupying the deep Champlain Valley and one or more occupying the valleys east of the Green Mountains. The transition from regional ice flow across the mountains to topographically guided ice flow migrated north as the ice sheet thinned.

A 65 km length of the of the Green Mountain ridgeline contains a younger set of striations with southwestern azimuths indicating that ice flow rotated from southeast to southwest across this area for a limited period of time. The ice sheet began flowing southwest, obliquely across the mountains, when the ice surface in the Champlain Valley lowered relative to that east of the mountains driving ice flow into the Champlain Valley. Fast ice flow, most likely a short-term period of ice streaming, is proposed as a mechanism for lowering the ice surface. This event began when the ice surface south of Pico Peak was too low to flow across the mountains. The area of fast flowing ice in the Champlain Valley migrated north as far as Appalachian Gap when conditions causing fast ice flow ceased. Accelerated flow would not only have lowered the ice surface but also caused the ice front to quickly advance. A readvance (the Luzerne Readvance) and a large kame and kettle terrane in the northern Hudson River valley may have resulted, respectively, from this period of fast ice flow and subsequent stagnation of the thinned ice when rapid ice flow stopped.

Ice flow became increasingly topographically controlled as the ice sheet thinned across this mountainous area. Most valleys are oriented north–south, parallel to the major mountain ranges and ice flow was consequently redirected south across large areas as the ice sheet thinned. However, the Winooski and Lamoille River valleys provided deep avenues for ice from the Champlain Valley to flow ESE across the mountains. A series of ice-dammed lakes in both the Winooski and Lamoille drainage basins provide evidence that the ice sheet east of the mountains retreated northwards much more rapidly than the ice sheet in the Champlain Valley.

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Appendix. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2015.10.018.

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