TESTING LATEST WISCONSINAN ICE FLOW DIRECTIONS IN VERMONT THROUGH QUANTITATIVE X-RAY DIFFRACTION ANALYSIS OF SOIL MINERALOGY

[1,2]Jeffrey S. Munroe, [1]Peter C. Ryan, [1]Holly A. Carlson, and [3]Eric K. Miller
[1]*Geology Department, Middlebury College, Middlebury, VT 05753*
[2]*jmunroe@middlebury.edu*
[3]*Ecosystems Research Group, Ltd., Norwich, VT 05055*

ABSTRACT: Quantitative X-ray diffraction (QXRD) was used to determine the direction of ice flow by the Laurentide Ice Sheet into northern Vermont during the latest Wisconsinan Glaciation by comparing the mineralogy of soil and glacial till from sites located to the southeast and southwest of notable concentrations of minerals (K-feldspar, serpentine, and chlorite). Sixty-nine samples were analyzed from sixteen soil pits distributed in two study areas in northeastern Vermont. Samples were also analyzed from two stratigraphic sections featuring superposed tills previously interpreted as representing discrete glacial advances. Results indicate that surficial deposits in northeastern Vermont were deposited by ice flowing from the northwest. These results contradict some previous mapping, which interpreted that the surficial sediment in this area was deposited by ice of a northeastern provenance, but provide support for studies that were critical of the northeasterly advance theory. The results of this project demonstrate the utility of QXRD as a tool for interpreting past ice flow directions and should improve the utility of models designed to predict the acid rain buffering potential of soils in this region.

INTRODUCTION

The glacial history of the northeastern United States has been studied for over 100 years, yet our understanding of the late Pleistocene history of this topographically complex region continues to evolve (e.g. Agassiz 1870; Hitchcock 1878; Goldthwait 1913; Lougee 1940; Stewart 1961; Thompson et al. 1999). The Last Glacial Maximum (LGM) Wisconsinan Glaciation reached its maximum extent in the northeastern United States ca. 23 ka BP (Balco et al. 2002) when the Laurentide Ice Sheet inundated all of Vermont, including the highest summits (~1300 m asl). Reconstructions of the Laurentide Ice Sheet suggest that ice flowed into the northeastern United States from the northwest at the LGM (e.g. CLIMAP 1976; Denton and Hughes 1981; Prest 1984; Marshall et al. 2000; Dyke et al. 2002; Marshall et al. 2002), and the overall pattern of striations supports a picture of regional northwest to southeast iceflow (Ackerly and Larsen 1987). Retreat began ~18 ka BP, and the state (200 to 450 km from the terminal moraine) was deglaciated by 13 ka BP (Ridge et al. 1999). Much of the surficial glacial sediment in Vermont was deposited during this deglacial period, and because underlying topography would have increasingly controlled the thinning ice, the direction of ice flow during retreat remains an interesting question. Most notably, Stewart (1961) and Stewart and MacClintock (1969) proposed that the last ice to cover much of Vermont advanced from the northeast in contrast to the flow direction at the LGM. On the basis of till fabric and striation measurements, they defined a stratigraphy of three drift sheets: a lower till derived from the northwest, a middle till derived from the northeast (the Shelburne Drift), and an uppermost till also derived from the northwest. As mapped, the ice responsible for deposition of the uppermost till only covered the western half of Vermont (see inset **Fig. 1)**, leaving the northeasterly-derived Shelburne Drift at the surface in much of the state (Stewart and MacClintock 1969, 1970).

Complex topography can certainly influence ice flow directions, especially during deglaciation, and this undoubtedly occurred in some parts of Vermont (e.g. Ackerly and Larsen 1987). However, such local effects cannot easily explain the regional extent of northeasterly-derived till mapped by Stewart and MacClintock (1970) in the eastern half of the state. Furthermore, while it is recognized that a major reorganization of ice flow occurred in northern Maine and southern Québec during the last deglaciation, the effects of this change were limited to areas more than 100 km to the north-northeast of Vermont (Lamarche 1971; Thomas 1977; Lowell 1985; Parent and Occhietti 1999). Finally, while glacial sediment apparently deposited by regional northeast to southwest ice flow is present to the north of Vermont in southern Quebec (the Chaudière till of McDonald and Shilts 1971), ice flow apparently shifted toward the southeast during deposition of this unit, and the Chaudière till is overlain by till that was derived from the northwest (McDonald and Shilts 1971; Shilts 1981; Lamothe et al. 1992).

Several unpublished graduate theses investigated aspects of the surficial geology of Vermont (e.g. Cannon 1964; Thomas 1964; Behling 1965; Shilts 1965) and many present conclusions contrary to those of Stewart and MacClintock (1969). Contemporary mapping has also challenged Stewart and MacClintock's interpretations, especially the work of Larsen (1972, 1987), Larsen and Koteff (1988), Springston and Haselton (1999), and DeSimone (2001, 2004, 2005, 2006a, 2006b). However, no attempt has been made to systematically test the hypothesis of a surficial northeasterly-derived till in northeastern Vermont, and Stewart and MacClintock's (1970) map remains the most accessible and prominent published reference on the glacial geology of this area. As mapped, therefore, the northeasterly-derived surface till presents a challenge to our understanding of the glacial history of the northeastern U.S., and the paleogeography and dynamics

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of the Laurentide Ice Sheet. Furthermore, this situation has recently developed a new dimension as researchers have begun to model the acid rain buffering potential of soils in New England and adjacent Canada (Forest Mapping Group 2003). The mineralogy of soil parent materials, inferred from till provenance, is a major input to these models, and uncertainty over the ice flow direction responsible for till deposition greatly complicates these modeling efforts. Although more recent fieldwork and unpublished theses suggest otherwise, researchers would be expected to rely on Stewart and MacClintock's (1970) official state mapping because the theory of a northeastern provenance for much of the surface till in Vermont has never been formerly tested beyond the local scale. Accordingly, a major goal of this study was to develop observational evidence that could improve these models by reducing the remaining uncertainty about ice flow directions in the area of Stewart and MacClintock's (1969) northeasterly-derived surface till.

Given the value in furthering our understanding of late Wisconsinan ice flow directions in northeastern Vermont, we tested the hypothesis that glacial sediment at the surface in this area was deposited by ice flow from the northeast. Our approach involved quantitative X-ray diffraction (QXRD) analysis of the mineralogy of surficial materials relative to bedrock outcroppings containing notable concentrations of serpentine, K-feldspar, and chlorite. This procedure allowed patterns of sediment redistribution resulting from glacial erosion and deposition to be identified and Stewart and MacClintock's (1969) model of till provenance in northeastern Vermont to be evaluated.

STUDY AREAS

Two study areas were selected on the basis of their position

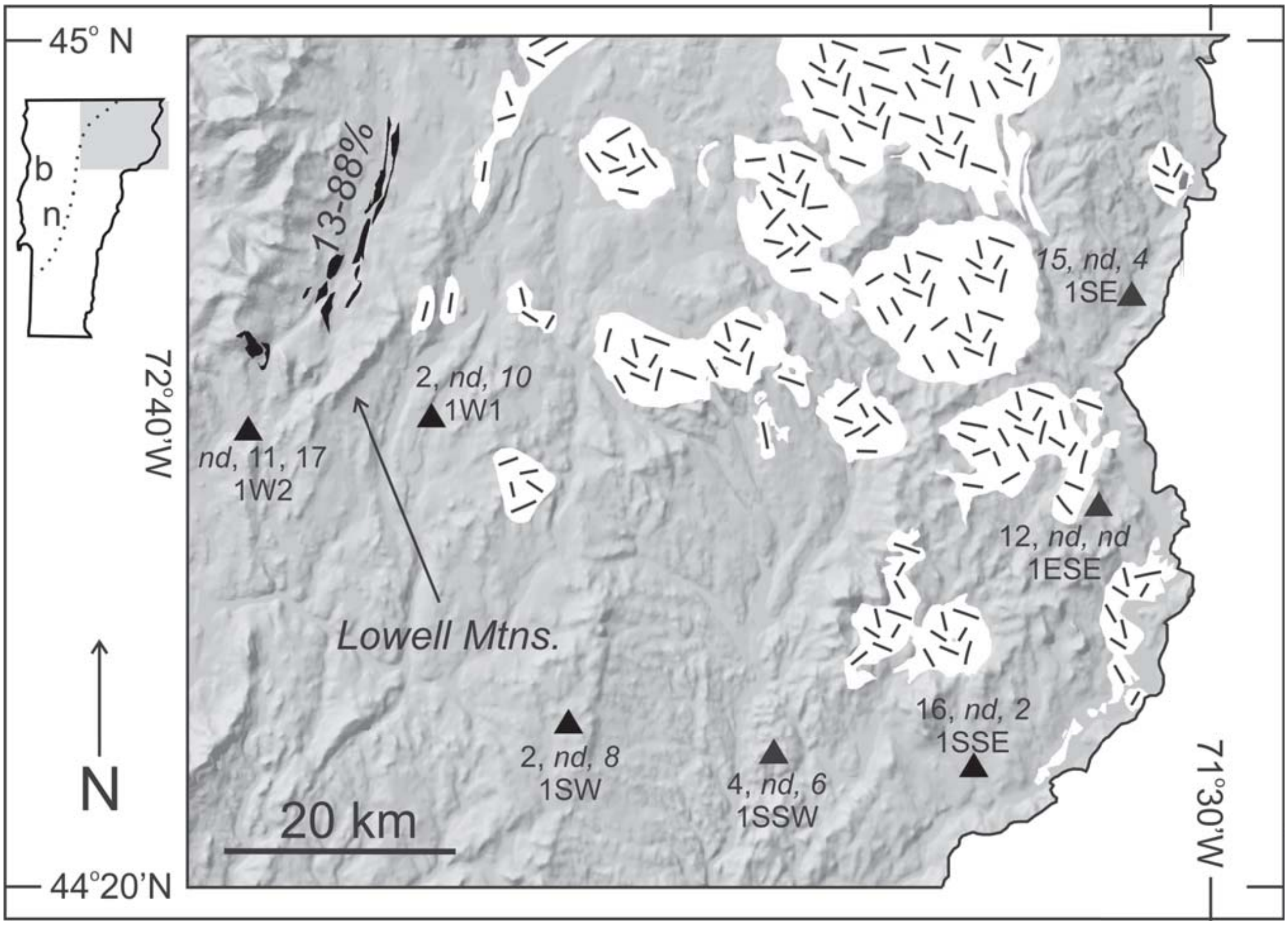


Figure 1. Map of Study Area 1 in northeastern Vermont, showing locations of soil pits (triangles) and plutons (irregular white shapes) overlain on a 30-m digital elevation model (DEM). Soil pits are noted with the convention: average K-feldspar %, average serpentine %, average chlorite % over Pit ID; "nd" is "not detected." Ultramafic rocks (irregular black shapes) contain 13 to 88% serpentine. Note the position of the Lowell Mountains, which may have deflected late-stage ice-flow in a SSW direction toward Pit 1W2. Inset marks location within Vermont; dotted line is the approximate boundary between the till of NW and NE provenance, and "b" and "n" are the locations of the exposures at Bostwick (b) and Notch Roads (n).

relative to the till sheets defined by Stewart and MacClintock (1969, 1970), and their location relative to bedrock (Doll et al. 1961) with notably high concentrations of traceable minerals **(Table 1)**. Study Area 1 (Fig. 1) was established to trace K-feldspar and serpentine in the vicinity of K-feldspar-rich (up to 50%) plutons and ultramafic rocks in a part of northeastern Vermont, while Study Area 2 **(Fig. 2)** was established to trace K-feldspar near the Knox Mountain (Barre) granitic pluton (30-40% K-feldspar). Country rock in both regions is generally chlorite- and muscovite-schist.

Two exposures of gray diamicton overlain by tan-to-orange diamicton were also sampled (Fig. 1). Similar “two-till” localities have featured prominently in the interpretation of the glacial stratigraphy of the region and considerable debate has focused on whether the superposed tills represent one or two glaciations (e.g. Stewart and MacClintock 1969; Borns and Calkin 1977; Koteff and Pessel 1985; Oldale and Colman 1992). Samples were taken from a 4-m high section along Bostwick Road (44º22’04”N, 73º14’38”W, “b” in Figures 1 and 2) in the Champlain Valley of western Vermont. Albite-chlorite schist outcrops 30 km northeast of this site but is absent north and northwest of the site (Stone and Dennis 1964), where bedrock consists of carbonate-, quartz- and illite-dominated Ordovician sedimentary rocks. A 12-m high exposure was also sampled along Notch Road (44º04’42”N, 73º03’53”W, “n” in Figures 1 and 2) on the western slope of the Green Mountains. Paleozoic meta-sedimentary rocks and localized granitic intrusives with 17 to 34% K-feldspar (Laurent and Pierson 1973) outcrop within 25 km to the northwest of this site, and extensive outcrops of albite-chlorite-mica schist are present to the northeast. As mapped by Stewart and MacClintock (1970), both of these localities should feature a northeasterly-derived till overlain by a till of northwestern provenance.

METHODOLOGY

Soil pits were excavated to depths of 60 to 115 cm, reaching either bedrock or dense parent material exhibiting no obvious signs of chemical weathering. Soil profiles were described using standard methods (Soil Survey Staff 1993). Coarse fragments were collected from each pit, and soil samples for mineralogy and bulk density were retrieved from each horizon. Samples were stored in sealed plastic bags at room temperature prior to lab analysis.

In the laboratory, samples were dried and sieved to separate the <2-mm (fine-earth) fraction. To quantify the mineralogy of the fine-earth fraction, zinc oxide was added as an internal standard. The soil and ZnO mixture (3.6 g : 0.4 g) was then combined with 10-15 ml of a 0.5% polyvinyl alcohol (PVA) solution (in distilled water) to create a slurry that was pulverized for 10 min in a McCrone Micronizing Mill, producing <10-μm particles with a narrow grain size distribution (Hillier 2000; Środoń et al. 2001). The resulting suspension was then spray dried into a 130 ºC chamber, producing a powder consisting of spheres 50-60 μm in diameter comprised of randomly-oriented mineral grains required for QXRD analysis (Hillier 1999). Spray dried

Table 1. Site characteristics for soil profiles.

Soil Pits	Latitude deg min sec	Longitude deg min sec	Elevation m	Clast Lithology	Vegetation
Study Area 1					
1W 1	44º 42' 47" N	72º 2' 51" W	525	quartzite, schist	northern hardwoods
1W 2	44º 41' 10" N	72º 32' 27" W	335	schist	confiers
1SW	44º 28' 28" N	72º 11' 45" W	625	phyllite	northern hardwoods
1SSW	44º 27' 01" N	71º 58' 35" W	380	schist, quartzite	northern hardwoods
1SSE	44º 25' 58" N	71º 43' 52" W	420	schist, granite	northern hardwoods
1SE	44º 48' 05" N	71º 35' 55" W	480	granite, schist	conifers
1ESE	44º 38' 19" N	71º 38' 34" W	412	granite	conifers
Study Area 2					
2WSW	44º 03' 06"N	72º 37' 52"W	556	schist	northern hardwoods
2SW	44º 08' 53"N	72º 32' 44"W	620	schist	mixed pine
2SSW	44º 02' 56" N	72º 23' 13" W	558	schist	northern hardwoods
2S	44º 09' 27" N	72º 23' 19" W	548	granite, quartzite	northern hardwoods
2SE 1	44º 11' 46"N	72º 12' 29"W	352	granite	conifers
2SE 2	44º 06' 46" N	72º 07' 38" W	375	schist, granite	conifers
2DSE	43º 59' 49"N	72º 08' 06"W	175	schist, granite	mixed hardwood, pine
2ESE	44º 10' 35" N	72º 18' 53" W	600	granite	northern hardwoods
2E	44º 11' 42" N	72º 19' 36" W	631	granite, schist	northern hardwoods

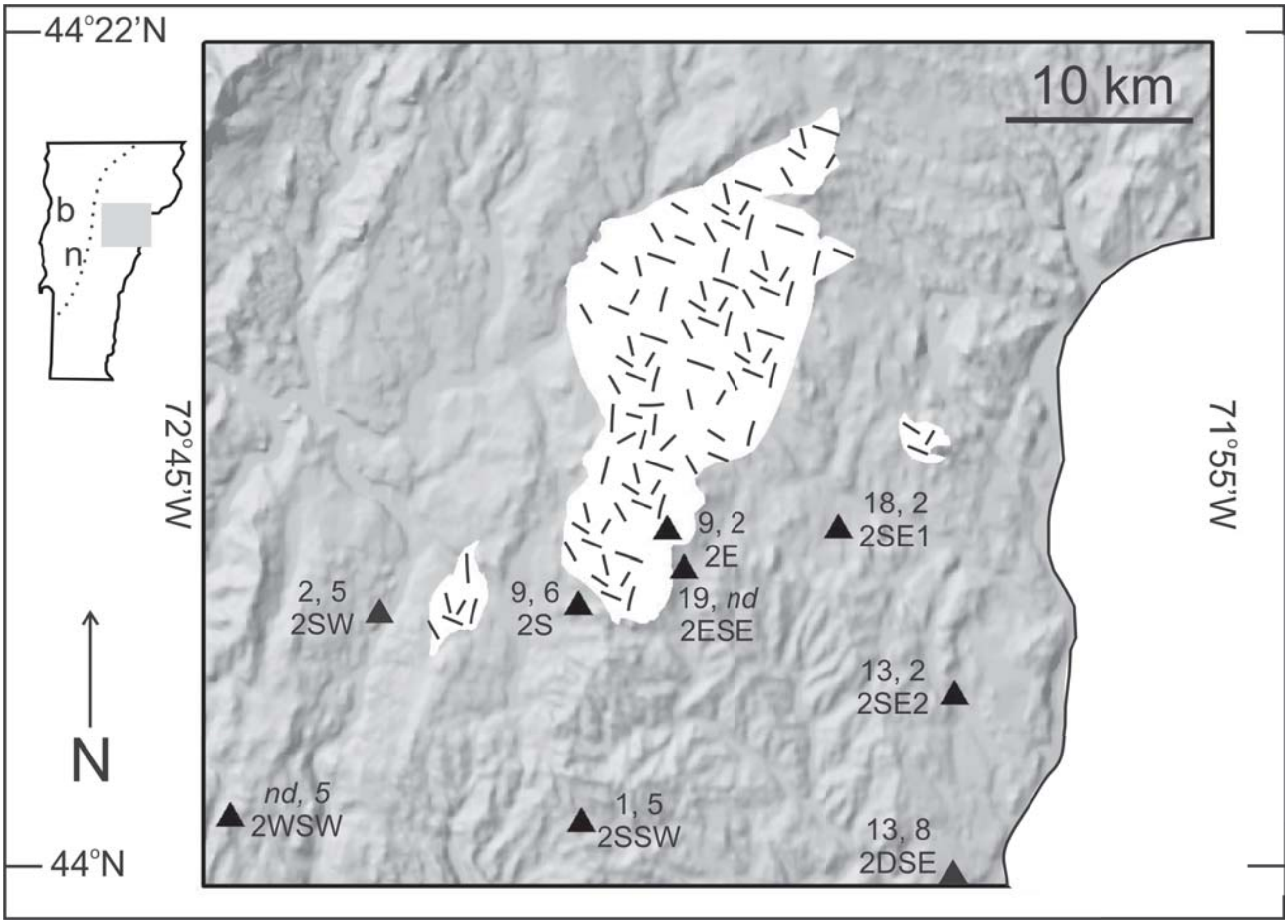
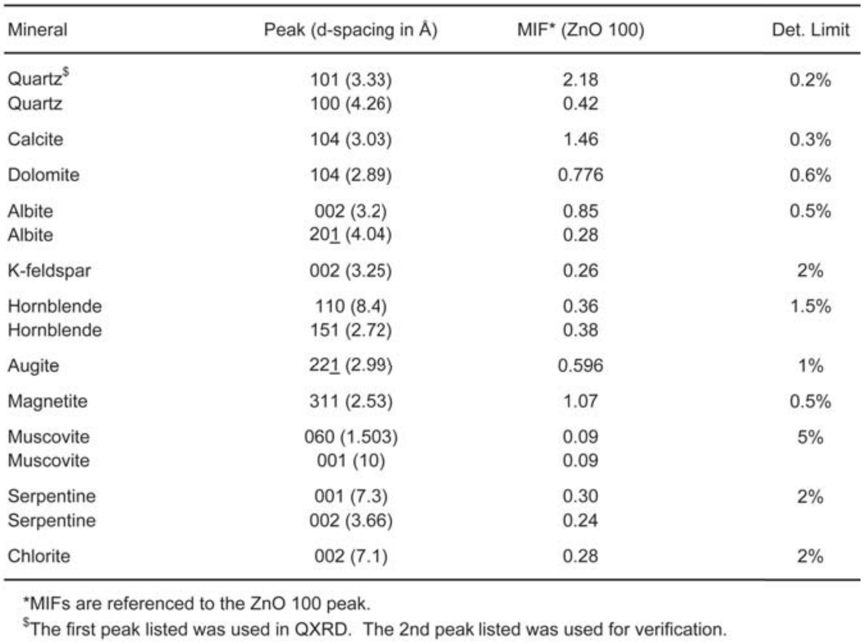


Figure 2. Map of Study Area 2 in east-central Vermont showing locations of soil pits (triangles) and granitic plutons (irregular white shapes) overlain on a 30-m DEM. Soil pits are noted with the convention: average K-feldspar % over Pit ID. "nd" indicates not-detected. Inset marks location within Vermont; dotted line is the approximate boundary between the till of NW and NE provenance, and "b" and "n" are the locations of the exposures at Bostwick (b) and Notch Roads (n).

powders were sprinkled onto a zero background quartz plate and analyzed in a Siemens D-500 X-ray diffractometer with CuKα radiation at 40 kV and 40 mA, an angular range of 2 to 70º, step interval of 0.05º and count time of 5 s per step. XRD peak intensity was determined by measuring integrated peak areas, and mineral proportions were quantified using mineral intensity factors (MIFs) developed in the Middlebury College XRD lab using ZnO and pure mineral specimens (Fisher and Ryan 2006; Munroe et al. 2006). In specimens with both K-feldspar and albite, an pure albite XRD pattern was digitally subtracted (using Jade® software; www.materialsdata.com) to remove interference of the albite 002 peak at 3.2 Å with the K-feldspar 040 peak at 3.25 Å, thus enabling more precise quantification of K-feldspar. With 95% confidence, uncertainty in mineral quantification is given by $\pm X^{0.35}$, where X = concentration in weight %. Examples of uncertainties using this formula are 5 ± 2%, 20 ± 3%, 50 ± 4% and 80 ±4%. Mineral peaks used in XRD quantification, MIFs, and detection limits are presented in **Table 2.** Profile mean quantities of K-feldspar, serpentine, and chlorite were determined by extending the lowest horizon to 100 cm (if necessary), weighting each horizon by its thickness, and normalizing to 100 cm.

In order to determine clay mineralogy, and to verify fine-earth fraction identification of muscovite and chlorite in particular, the <2-µm fraction was isolated from each sample by gravity settling following ultrasonic disaggregation in a suspension with Na-hexametaphosphate. Oriented mounts of all samples were prepared by the membrane peel method of Drever (1973) and were analyzed by XRD from 2 to 40º at a step size of 0.05º and a count time of 2 s, first in the air-dried state and subsequently in ethylene glycol-solvated (60ºC, 24 h) and heated (250ºC, 1 h) states. Muscovite and biotite were identified by characteristic intensities of 10-Å 001 peaks as compared to 5-Å 002 peaks (Moore and Reynolds 1997). Chlorite was distinguished from kaolinite by the characteristic 3.54-Å chlorite 004 peak as compared to the 3.58-Å kaolinite 002 peak. Trioctahedral clays such as vermiculite, hydrobiotite and biotite were observed in clay fractions of some specimens, but are only present in fine-earth fractions at concentrations below detection limits

Table 2. XRD peaks and mineral intensity factors.



Mineral	Peak (d-spacing in Å)	MIF* (ZnO 100)	Det. Limit
Quartz[$]	101 (3.33)	2.18	0.2%
Quartz	100 (4.26)	0.42	
Calcite	104 (3.03)	1.46	0.3%
Dolomite	104 (2.89)	0.776	0.6%
Albite	002 (3.2)	0.85	0.5%
Albite	$20\underline{1}$ (4.04)	0.28	
K-feldspar	002 (3.25)	0.26	2%
Hornblende	110 (8.4)	0.36	1.5%
Hornblende	151 (2.72)	0.38	
Augite	$22\underline{1}$ (2.99)	0.596	1%
Magnetite	311 (2.53)	1.07	0.5%
Muscovite	060 (1.503)	0.09	5%
Muscovite	001 (10)	0.09	
Serpentine	001 (7.3)	0.30	2%
Serpentine	002 (3.66)	0.24	
Chlorite	002 (7.1)	0.28	2%

*MIFs are referenced to the ZnO 100 peak.

[$] The first peak listed was used in QXRD. The 2nd peak listed was used for verification.

(<5%), so were not quantified. These same is true for kaolinite, which was observed locally in the clay fraction of B-horizons but is present in fine-earth fractions at concentrations below the detection limit of 3%.

RESULTS

Details of the mineralogy of all 69 samples are presented in **Table 3**. Profile means of K-feldspar, serpentine, and chlorite in each of the 16 soil profiles are given in **Table 4**. Results from the two-till sites at Bostwick Road and Notch Road are presented in **Table 5. Figures 3 and 4** present X-ray diffraction data representative of the mineralogical variability observed throughout the study area.

Study Area 1

K-feldspar values were uniformly low (profile average of 0 to 4%) in the four soil profiles (1W1, 1W2, 1SW, and 1SSW) located to the south and west of the K-feldspar-bearing plutons in northeastern Vermont (Fig. 1, Table 4). In contrast, the three pits to the east and southeast of the plutons (1SE, 1ESE, and 1SSE) contained 9 to 18% K-feldspar by horizon and overall profile averages from 12 to 16%. Chlorite contents were higher in Pits 1W1 and 1W2 located southwest of the plutons (10% and 17% respectively, by profile). Serpentine was only detected in pit 1W2 located 5 km south-southwest of the ultramafic rocks. Here the C-horizon contained 12% serpentine and the overall profile weighted average was 11%.

Study Area 2

All samples contained high concentrations of K-feldspar (5 to 23%, profile averages 9 to 19%) with the exception of those from 2SSW (profile average 1%), 2SW (2%) and 2WSW (not detected) located south and southwest of the Knox Mountain granitic pluton (Figs. 2, 3) (Table 4). Albite content per horizon was also lower in these three pits, ranging from 4 to 12% compared to 10 to 23% in the six pits east and southeast of the plutons (Table 3). Chlorite content was greater in 2SSW, 2WSW, 2SW and 2S (5 to 6% by profile) than in other profiles ("nd" to 3%), except for 2DSE (8%).

Two-Till Sites

QXRD analysis of the fine-earth fraction of samples collected from the Bostwick Road exposure revealed little mineralogical difference between the two tills (Fig. 4) (Table 5). Both samples are dominated by quartz (25 and 38%) and muscovite (32 and 51%), contain only minor amounts of albite (<2%) and K-feldspar (<3 %), and lack chlorite. The most distinct difference in mineralogy between the two samples is the presence of calcite (5%) in the lower till and its absence in the oxidized upper till.

A similar situation was noted in the superposed tills from Notch Road (Fig. 4) (Table 5). High amounts of quartz were found in both upper (52%) and lower (64%) tills. K-feldspar constituted 18% of the upper till and 12% of the lower till, and small amounts of albite (<2 to 4%) were observed in both samples. The upper till at Notch Road contains no calcite or dolomite, but the lower till contains 1% and 9% of these minerals, respectively.

Table 3. Mineral percentages for individual Soil Profiles.

Sample$	QTZ	CAL	AB	Kfs	HBL	AUG	MAG	MS	SRP	CHL	TOTAL**
Pit 1W2 (South-southwest of ultramafic rocks)											
S4	40.4	0	2.6	0	3.7	0	0	11.1	10.4	9.1	77.3
S3	34.2	0	3.6	0	1.4	0	0	12.2	6.3	9.5	67.2
S2	38.8	0	13.4	0	3.2	0	0	9.2	11.4	20.2	96.2
S1	32.1	0	11.2	0	7.1	0	0	16.9	11.6	20.9	99.8
Pit 1W 1 (West-southwest of plutons, southeast of serpentinite)											
S4	31.7	0	4.8	tr	0	0	0.4	9.9	0	7.1	53.9
S3	34.7	0	5.6	tr	0	0	0.6	10.9	0	4.1	55.9
S2	43.2	0	9.1	2.3	0	0	0.4	15.4	0	8.9	79.3
S1	38.1	0	11.5	3.0	1.4	0	0.4	14.2	0	13.1	81.7
Pit 1SW (Southwest of K-feldspar-rich plutons)											
S4	33.1	0	4.1	tr	0	0	0	5.2	0	3.1	45.5
S3	17.5	0	3.9	tr	0	0	0	5.7	0	7.5	34.6
S2	31.9	0	7.1	4.3	0	0	0	8.1	0	6.4	57.8
S1	38.0	0	8.6	2.1	2.7	0	0	5.9	0	11.4	68.7
Pit 1SSW (South-southwest of K-feldspar-rich plutons)											
S4	38.6	0	11.8	5.5	0.0	2.1	0	7.6	0	3.2	68.8
S3	39.8	0	11.4	4.1	1.7	2.0	0	6.7	0	5.1	70.8
S2	40.4	0	13.4	2.8	0.0	3.5	0	12.2	0	7.1	79.4
S1	43.2	0	16.4	3.6	0.0	5.1	0	24.2	0	6.6	99.1
Pit 1SSE (Southeast of K-feldspar-rich plutons)											
S5	44.6	0	12.7	14.2	1.4	1.9	2.1	5.2	0	tr	82.1
S4	30.6	0	14.0	12.4	2.4	2.3	3.1	6.5	0	tr	71.3
S3	31.8	0	19.3	16.3	2.4	3.0	3.6	6.9	0	tr	83.3
S2	32.2	0	19.5	13.9	3.2	3.9	2.9	6.6	0	2.5	84.7
S1	33.6	0	20.1	18.2	3.1	3.6	2.5	8.1	0	3.3	92.5
Pit 1SE (Southeast of K-feldspar-rich plutons)											
S4	35.7	0	11.2	15.9	3.7	0	0	8.9	0	0	75.4
S3	48.3	0	16.7	8.4	1.4	0	0	10.7	0	2.7	88.2
S2	38.8	0	13.4	11.5	3.2	0	0	9.5	0	3.1	79.5
S1	42.5	0	13.9	18.1	7.1	0	0	9.4	0	5.6	96.6
Pit 1ESE (East-southeast of K-feldspar-rich plutons)											
S5	40.9	0	11.7	17.1	0	0	0	9.9	0	0	79.6
S4	38.9	0	18.2	15.2	0	0	0	6.2	0	0	78.5
S3	25.2	0	20.5	10.9	0	0	0	11.6	0	0	68.2
S2	24.9	0	22.4	15.8	4.6	0	0	10.2	0	0	77.9
S1	27.5	0	30.2	9.2	4.9	0	0	9.6	0	0	81.4
Pit 2WSW (Distal southwest of K-feldspar-rich plutons)											
S3	49.7	0	7.5	0	0	0	0	21.4	0	8.2	86.8
S2	67.4	0	11.6	0	0	0	0	19.1	0	2.1	100.2
S1	67.2	0	6.9	0	0	0	0	19.3	0	3.9	97.3
Pit 2SW (Southwest of K-feldspar-rich plutons)											
S4	41.2	0	7.7	3.2	0	0	0	9.5	tr	3.1	64.7
S3	43.1	0	8.9	0	0	0	0	17.3	0	4.7	74.0
S2	54.8	0	8.3	1.8	0	0	0	tr	0	tr	64.9
S1	42.1	0	7.2	3.9	0	0	0	27.1	0	10.2	90.5

Table 3. Mineral percentages for individual Soil Profiles (continued).

Sample$	QTZ	CAL	AB	Kfs	HBL	AUG	MAG	MS	SRP	CHL	TOTAL**
Pit 2SSW (South-southwest of K-feldspar-rich plutons)											
S4	32.1	0	4.3	tr	0	0.3	0.5	10.1	0	0	47.3
S5	76.7	0	7.6	2.9	0	0.3	0.5	10.2	0	0	98.2
S6	51.1	0	8.9	3.3	6.9	0.3	0.6	15.6	0	3.4	90.1
S7	53.1	0	7.8	0	5.8	0.4	0.5	13.2	0	6.1	86.9
Pit 2S (Southern border of of K-feldspar-rich plutons and Devonian metasediment)											
S5	51.2	0	13.9	7.8	tr	0	tr	8.6	0	7.6	89.1
S4	58.9	0	15.3	7.6	tr	0	tr	9.6	0	7.6	99.0
S3	59.5	0	17.6	10.7	tr	0	tr	6.4	0	4.1	98.3
S2	64.5	0	14.6	5.2	tr	0	tr	10.7	0	6.6	101.6
S1	53.8	0	13.6	9.5	2.2	0	tr	8.2	0	4.3	91.6
Pit 2SE1 (East-southeast of K-feldspar-rich plutons)											
S5	54.7	0	15.1	9.7	0	0	0.6	tr	0	0	80.1
S4	67.4	0	15.1	10.2	0	0	0.5	tr	0	0	93.2
S3	64.5	0	11.3	23.4	0	0	0.8	tr	0	0	100.0
S2	54.1	0	21.4	16.9	0	0	0.6	tr	0	tr	93.0
S1	48.6	0	22.7	17.7	0	0.8	0.7	tr	0	3.8	94.3
Pit 2SE2 (Southeast of K-feldspar-rich plutons)											
S4	47.2	0	15.6	9.4	1.6	0	1.6	tr	0	tr	75.4
S3	38.3	0	19.3	11.8	1.6	0	1.4	3.4	0	2.1	77.9
S2	41.2	0	21.3	14.6	1.7	0	1.5	2.5	0	3.8	86.6
S1	41.7	0	20.4	12.3	1.8	0	2.2	3.2	0	3.1	84.7
Pit 2DSE (Distal southeast of K-feldspar-rich plutons)											
S5	52.6	0	16.1	5.3	0	0	0	tr	tr	0	74.0
S4	54.6	0	16.9	3.9	0	0	0	tr	tr	0	75.4
S4	38.0	0	11.1	13.1	0	0	0	9.6	0	4.2	76.0
S2	41.9	0	12.1	16.4	0	0	0	10.3	0	14.6	95.3
S1	46.2	0	20.1	13.5	tr	0	0	8.2	0	10.3	98.3
Pit 2ESE (East-southeast of K-feldspar-rich plutons)											
S5	70.4	0	9.5	11.7	tr	0	tr	5.3	0	0	96.9
S4	51.8	0	17.6	15.3	tr	0	tr	3.2	0	tr	87.9
S3	69.7	0	15.1	14.9	2.1	0	tr	tr	0	tr	101.8
S2	60.7	0	15.6	18.8	tr	0	tr	3.1	0	tr	98.2
S1	57.5	0	18.1	21.8	tr	0	tr	4.9	0	tr	102.3
Pit 2E (East of K-feldspar-rich plutons)											
S4	71.6	0	12.3	8.5	tr	0	tr	6.3	0	tr	98.7
S3	72.2	0	10.2	6.7	tr	0	tr	10.8	0	tr	99.9
S2	74.9	tr	13.4	10.1	tr	0	tr	tr	0	tr	98.4
S1	64.9	1.1	15.5	8.4	tr	0	tr	3.5	0	3.1	96.5

$Samples are arranged in stratigraphic order.

*Minerals: Quartz (QTZ), calcite (CAL), dolomite (DOL), albite (AB), K-feldspar (Kfs), hornblende (HBL), augite (AUG), magnetite (MAG), muscovite (MS), serpentine (SRP), and chlorite (CHL).

**Low totals reflect the presence of amorphous solids including organic matter. Totals >100% likely are due to slight variability in mineral compositions that result in MIFs that differ from minerals used as standards.

"tr": minerals were detected only in clays fractions, or intensities in bulk QXRD are < 3σ above background.

DISCUSSION

Quantitative X-ray diffraction (QXRD) analysis of 69 samples gathered from 16 soil pits across northeastern Vermont reveals three end-member till compositions that reflect the signature of different source rocks (Table 4): (1)

Table 4. Weighted average mineral contents in soil pits.

	1W2	1W1	1SW	1SSW	1SSE	1SE	1ESE	2WSW	2SW	2SSW	2S	2SE1	2SE2	2ESE	2DSE	2E
K-feldspar	nd**	2	2	4	16	15	12	nd	2	1	9	18	13	19	13	9
Serpentine	11	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Chlorite	17	10	8	6	2	4	nd	5	5	5	6	2	2	nd	8	2
Signature$	U	S	S	S	G	G	G	S	S	S	SG	G	G	G	SG	SG
n^	4	4	4	4	5	4	5	3	4	4	5	5	4	5	5	4

*Profile values determined by weighting mineral percentages in individual horizons by profile thickness and extending lowest horizon to 100 cm (if necessary).

**"nd" denotes minerals not present in detectable quantities

$ G = Granite-derived, S = Schist-derived, U = Ultramafic-derived

^ "n" is the number of horizons sampled per profile.

Table 5. Mineralogy of two-till exposures.

	QTZ	AB	Kfs	HBL	MS	CHL	CAL	DOL	TOTAL$
Bostwick Road									
Upper	38	1	3	nd**	32	nd	nd	nd	73
Lower	25	2	2	nd	51	nd	5	nd	85
Notch Road									
Upper	52	2	18	nd	9	nd	nd	nd	80
Lower	64	4	12	nd	7	nd	1	9	96

*Minerals: Quartz (QTZ), albite (AB), K-feldspar (Kfs), hornblende (HBL), muscovite (MS), chlorite (CHL), calcite (CAL), and dolomite (DOL).

$Low totals reflect the presence of amorphous solids including organic matter.

**"nd" denotes minerals not present in detectable quantities

K-feldspar-rich till primarily derived from granitic plutons; (2) serpentine-bearing till influenced by ultramafic rock sources; and (3) chlorite-rich tills derived from schists of the Green Mountains. In areas where distinctive mineralogical sources (i.e. granite, 1 or serpentine, 2 above) are absent, schist-dominated assemblages (signature 3) characterize till mineralogy (e.g. pits 1SW, 1W1, 1SSW, and 2WSW). Otherwise, redistribution of bedrock-derived minerals indicates a northwest provenance for the till. Most notably, at Study Area 1, soil profiles to the south and southwest of K-feldspar rich plutons contain <4% K-feldspar whereas profiles east and southeast of the plutons contain up to 16% of this mineral. At Study Area 2, soils to the southwest of the Knox Mountain granitic pluton contain <2% K-feldspar, whereas soil profiles south and southeast of the plutons have K-feldspar concentrations ranging from 9 to 19%. Chlorite content in soils of both study areas generally decreases with distance (eastward) from the Green Mountains. Together these results indicate pervasive northwest to southeast ice flow during deposition of the surficial till.

Evidence for northwest to southeast ice flow is notable because the majority of these samples were collected where the Shelburne Drift was mapped as the surface unit (Stewart and MacClintock 1969; 1970). The mineralogy of these soils, however, is inconsistent with the proposed northeastern provenance of the Shelburne Drift, and support challenges to the Stewart and MacClintock (1969) model presented by Larsen (1972, 1987) and Springston and Haselton (1999).

The only significant evidence for southwest-directed ice flow is the presence of considerable serpentine (weighted average 11%) in Pit 1W2, located south-southwest of the serpentinite outcrops, and its absence in till 10 km southeast of these rocks (Pit 1W1, Fig. 1). It is possible that additional sources of serpentine to the northwest of Pit 1W2 are obscured by glacial sediment. In this case the mineralogy of soil 1W2 would conform to the overall picture of ice flow from northwest to southeast. Alternatively, the northeast-trending Lowell Mountains (~350 m relief) located between the serpentinite outcrops and Pit 1W1 (Fig. 1), may have locally deflected ice flow during the waning stages of the Wisconsinan Glaciation, producing a local surficial unit of north-northeastern provenance. Similar local departures from the regional flow direction in response to topography have been noted in the region by Shilts (1973) and by Ackerly and Larsen (1987).

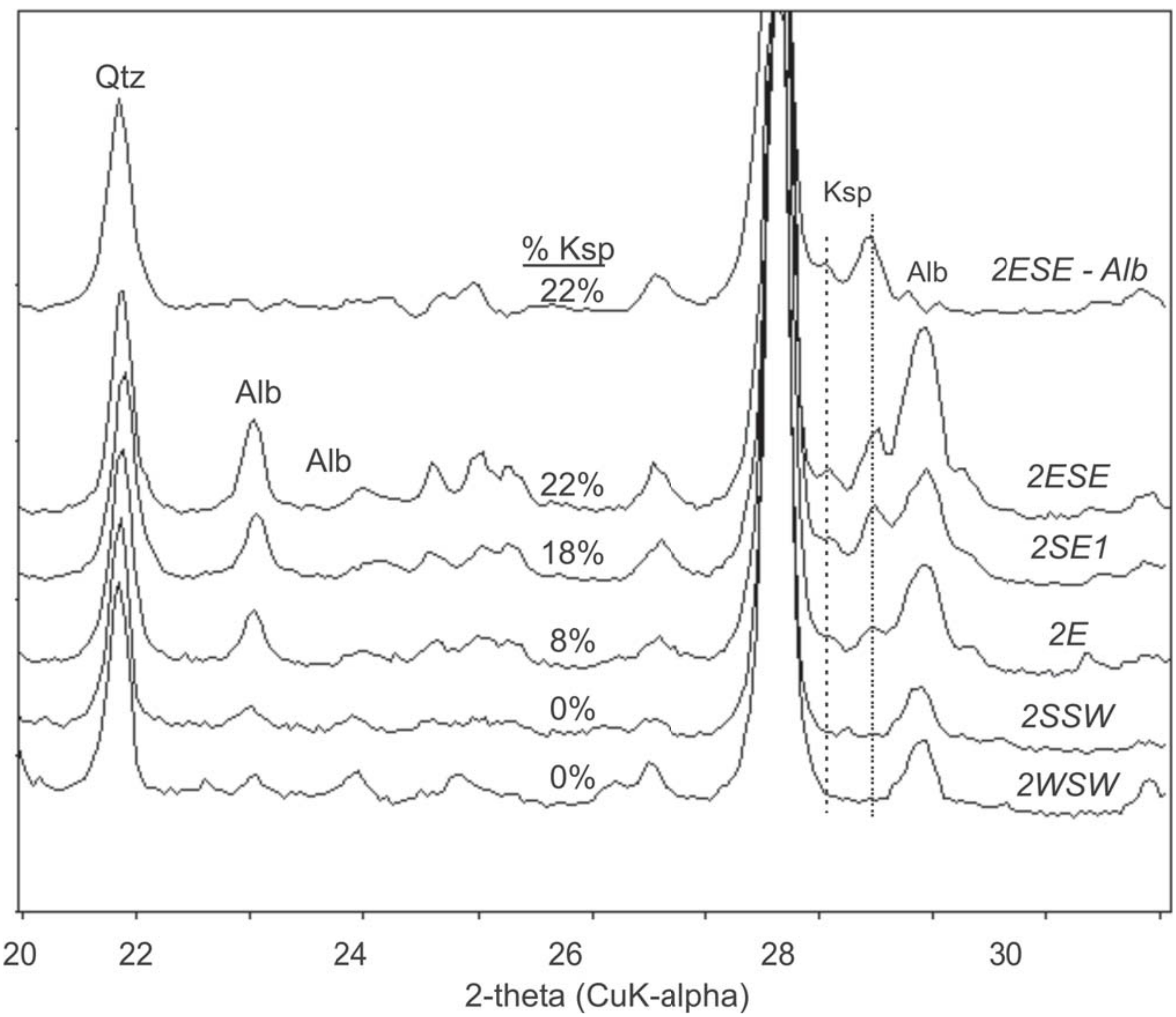


Figure 3. QXRD patterns of the <2-mm fraction of C horizon samples from soil profiles located southwest and southeast of the plutons in Study Area 2. Albite was digitally subtracted from the top pattern (2E-S1) to enhance quantification of K-feldspar using the 3.25 Å peak at 27.5 2º-theta. Wt % K-feldspar is denoted for each sample. Note the absence of K-feldspar in pits SW of the plutons (2SSW and 2WSW).

Analysis of samples from the two-till sequences at the Bostwick Road and Notch Road exposures also argues against ice flow from the northeast. The lower tills at both sites are consistently dark and fine-grained, while the upper tills are reddish-orange and sandy. This distinction may have led previous investigators to assign the units to discrete glacial advances, which would have come from the northeast (lower) and northwest (upper) in Stewart and MacClintock's (1969) model. However, the mineralogy of the upper and lower tills at both sites differs primarily in carbonate content, which was likely removed from upper tills by weathering. Furthermore, chlorite and albite are abundant in schist to the northeast of Bostwick Road, but chlorite is absent and albite is present only in small amounts (<2%) in tills at this site, arguing against a northeast provenance. This result supports the work of Thomas (1964) who concluded that the basal gray and upper brown tills in northwestern Vermont differed primarily in their degree of oxidization. Similarly, the mineralogy of the upper and lower tills at the Notch Road site reflects the presence of meta-sedimentary rocks rich in muscovite and quartz and a K-feldspar-bearing pluton to the northwest. The absence of chlorite at Notch Road further indicates that this till was not derived from chlorite schists present to the northeast. Thus, the supposed two-till sequences represent a weathering profile developed in a single till of northwesterly provenance.

These results are supported by other landforms and sediments in the northeastern U.S. that indicate ice advance from the northwest during the late Wisconsinan Glaciation. Larsen (1972) defined a fan of Knox Mountain (Barre)

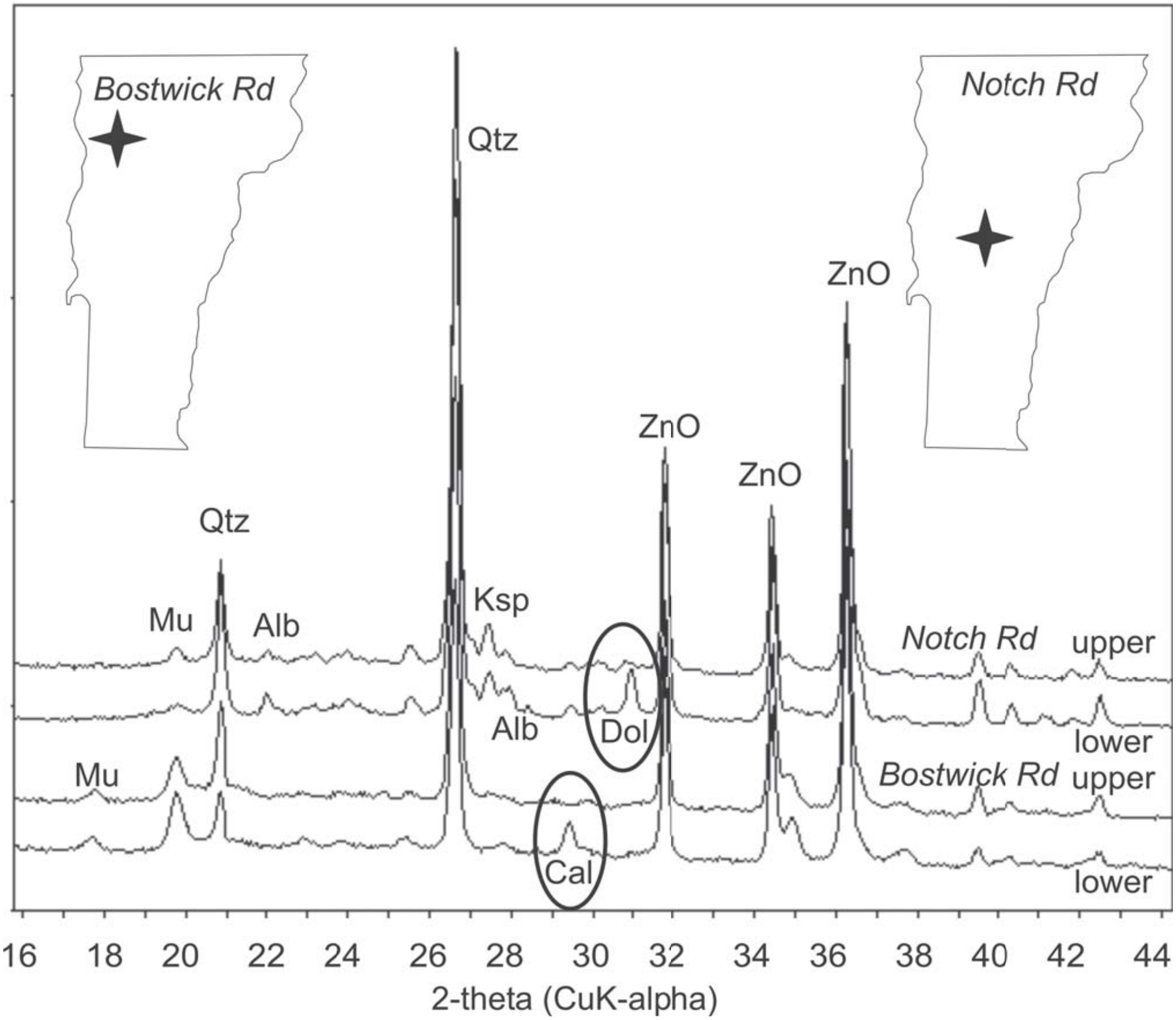


Figure 4. QXRD patterns of the <2-mm fraction of upper and lower tills from Bostwick Road and Notch Road (insets mark approximate locations). The only significant difference between the upper and lower tills is the presence of dolomite and calcite in the lower unoxidized till, and absence of carbonate minerals in upper oxidized till (circled). ZnO = zinc oxide (used as internal standard for mineral quantification).

Granite pebbles with a long axis trending S15ºE and a related 16-km long boulder train trending S5ºE. Numerous other indicator fans in both Vermont and New Hampshire trend from due south to S40ºE (Larsen 1972; Ackerly and Larsen 1987; Larsen et al. 2004). Dispersal patterns of glacial erratics, traceable minerals (magnetite), and trace metals (chromium and nickel) in the Lac-Mégantic region of southern Québec also indicate regional northwest to southeast ice flow during deposition of the late-Wisconsinan Lennoxville till (Shilts 1973). Drumlins in southern Vermont are oriented predominantly to the south-southeast (Ridge 1988), although some in southwestern Vermont are oriented to the south-southwest, likely reflecting the influence of local topography on ice flow during retreat (DeSimone and Dethier 1992). Finally, as noted earlier, the regional striation pattern in the northeastern U.S. reveals a predominant northwest to southeast trend (Ackerly and Larsen 1987). Localized exceptions to this pattern are noted in lowland settings where striations patterns show some conformity with topography, and along the crest of the Green Mountains in south-central Vermont where cross-cutting striations suggest a late glacial ice flow reversal to the southwest (Hitchcock et al. 1861; Hitchcock 1904; Goldthwait 1916; Ackerly and Larsen 1987). Stewart and MacClintock (1969) used these spatially restricted occurrences along with till fabric measurements to argue for a widespread late Wisconsinan advance from the northeast. However, given the convergence of evidence, these directional indicators may be better explained as local, topographically influenced, departures of late-stage ice flow within an overall pattern of regional southeastward ice movement. The results reported here provide definitive support for other, more local, studies that challenged the theory of a northeastern provenance for the surface till in much of the state (e.g. Larsen 1972, 1987; Larsen and Koteff 1988; Springston and Haselton 1999; DeSimone 2001, 2004, 2005, 2006a, 2006b), and strongly suggest that ice flowing into northeastern Vermont during the waning stages of the Wisconsinan Glaciation came from the northwest.

CONCLUSIONS

Mineralogical analysis of soil and soil parent material by QXRD argues against the theory that the last glacial advance into northeastern Vermont came from the northeast. In two study areas, notable concentrations of minerals (especially K-feldspar from granitic plutons) could be traced only to the southeast from known bedrock sources. In only one situation was a distinctive parent rock mineral traceable to the southwest (serpentine, Pit 1W2), an occurrence that can be attributed to the influence of local topography on the flow direction of thinning ice during deglaciation.

This conclusion counters the findings of Stewart and MacClintock (1969), who proposed that the last glacial ice in northeastern Vermont flowed from the northeast. These results are, however, consistent with studies at more local scales that criticized the Stewart and MacClintock model (e.g. Cannon 1964; Thomas 1964; Behling 1965; Shilts 1965; Larsen 1972, 1987; Larsen and Koteff 1988; Springston and Haselton 1999; DeSimone 2001, 2004, 2005, 2006a, 2006b). Overall iceflow from the northwest is also consistent with the general trend of boulder trains, indicator fans, drumlins, glacial troughs, and striations across the state, which almost universally indicate a northwest to southeast ice flow direction throughout the late Wisconsinan Glaciation. Southwest-trending striations and till fabrics, considered by Stewart and MacClintock (1969) as evidence for an ice advance from the northeast, are better explained by local topographically controlled ice flow.

The results of this study have broader implications for our understanding of the paleogeography and dynamics of the Laurentide Ice Sheet during the waning stages of the Wisconsinan Glaciation. Advance of ice into northeastern Vermont from the northeast is clearly inconsistent with radial ice flow outward from either a single- or multi-dome Laurentide Ice Sheet (e.g. CLIMAP 1976; Denton and Hughes 1981; Prest 1984; Marshall et al. 2000; Dyke et al. 2002; Marshall et al. 2002). The results reported here, however, support reconstructions of the Laurentide Ice Sheet that involve northwest to southeast ice flow into the northeastern U.S. during final stages of the Wisconsinan Glaciation, and provide an important constraint on ice flow directions.

These results will also be of use to researchers attempting to model the acid rain buffering potential of soils in this region, because mineralogy deduced from till provenance is a major input to these models. Bedrock units high in calcium carbonate are found in the upper Connecticut River Valley along the eastern border of the state, and the Stewart and MacClintock (1969) model predicts that much of the surficial sediment in northeastern Vermont was derived from these units. If, however, till in this area was derived from non-carbonate rocks to the northwest, as appears likely from the results reported here, then models based on Stewart and MacClintock's (1970) mapping would overestimate the acid rain buffering potential of large areas of eastern Vermont.

The conclusion of this research should be tested by additional studies with three main goals. First, specific areas for which Stewart and MacClintock (1969) reported tills with northeast-southwest fabrics should be revisited to determine how the mineralogy of these surficial sediments compares to the known distribution of nearby bedrock lithologies. This process might help reconcile the apparent discrepancy between the ice flow directions they inferred from fabric and those inferred here from till mineralogy. Second, other areas with dramatic local topography, similar to the Lowell Mountains region (Study Area 1), should be explored to develop a more complete understanding of the scale at which late-stage, topographically influenced, ice flow is responsible for the distribution for surficial sediments in Vermont. Finally, parts of southwestern Vermont should be investigated with the same methodology. Stewart and MacClintock's (1970) map shows northeasterly derived till across much of the southwestern part of the state. However, they note in their report (Stewart and MacClintock 1969) that other researchers active in the region during their mapping campaign rejected the theory that tills in this area were deposited by ice flowing from the northeast, primarily because clasts of Precambrian bedrock found in south-central Vermont are lacking in the surficial sediment. Shilts and Behling (1967) considered the northeast-southwest oriented till fabrics reported for this area an indication of topographically controlled ice flow, similar to the results reported here for sites to the north and northeast. Additional fieldwork in these areas would build upon existing mapping (Shilts and Behling 1967; Behling 1966; Shilts 1966a, 1966b; DeSimone 2001, 2004), and, ideally, lead to a unified view of ice flow directions in Vermont from the LGM through the waning stages of the Wisconsinan Glaciation.

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