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Alpine soil parent materials and pedogenesis in the Presidential Range of New Hampshire, U.S.A.

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Abstract

Previous work has explored the contribution of bedrock weathering to soil formation in alpine environments of the northeastern United States. In contrast, the role of surficial sediments as a parent material has received little attention. This study investigated the development of alpine soils in relation to surficial sediments and bedrock in part of the Presidential Range of the White Mountains, New Hampshire, U.S.A. Published mapping of the study area indicates that five contrasting bedrock units are thinly mantled by glacial sediment, providing the opportunity to evaluate the relative importance of these two potential soil parent materials. Samples collected from 25 pedons were analyzed for a variety of physical, chemical, and mineralogical properties. Soil profiles have distinct Oa, A, Bw, and BC horizons. X-ray diffraction analysis reveals the presence of chlorite in soils above all bedrock formations, despite the absence of this mineral in several bedrock types. Trace element concentrations are relatively uniform for all soils with no clear relationship to underlying bedrock. Differences in median grain size are significant in soils over different bedrock formations; however, extractable cations, cation exchange capacity, exchangeable acidity, and other soil properties exhibit no significant differences. The overall similarity of soils above strongly contrasting bedrock formations indicates that these soils are forming in a homogenous mantle of glacial sediment deposited in the late Wisconsin, and that bedrock weathering does not contribute to pedogenesis to measurable degree in this setting. Preservation of glacial sediment in the study area may be a function of the amount originally deposited, reduced erosion rates on relatively gentle slopes, or another unidentified factor.

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Introduction

Due to a convergence of climatic and edaphic factors, treeline in the northern Appalachian Mountains is lower than anywhere else in the contiguous United States, with an average elevation of ~1200 m. The total area of above-treeline habitat in this region is minor (~34 km^2, Kimball and Weihrauch, 2000), yet focused study of these scattered alpine zones over more than a century has yielded significant scientific contributions. For example, botanists have investigated the distributions of plants in these environments (e.g., Pease, 1924; Antevs, 1932; Bliss, 1963), identifying some that are extremely rare, such as *Potentilla robbinsiana* (dwarf mountain cinquefoil), which is endemic to the White Mountains of New Hampshire. Seminal works on alpine geomorphology and bedrock geology have been conducted in these mountains, yielding important information about the relative timing of continental and alpine glaciation (e.g., J. W. Goldthwait, 1913; R. P. Goldthwait, 1970) and Paleozoic orogenies (e.g., Billings, 1941; Eusden et al., 1996). The ongoing efforts of the Mount Washington Observatory, which maintains a continuously staffed weather station on the highest summit in the region, have contributed to understanding of alpine climate and climate change (e.g., Seidel et al., 2009). It has even been proposed that long-term monitoring of northern Appalachian alpine zones could establish a baseline upon which effects of future climate warming might be identified (Kimball and Weihrauch, 2000).

In contrast, soils of the northeastern Appalachian alpine zones have been studied to a more modest degree. A trio of unpublished graduate theses in the 1960s focused on alpine soils in Maine (Bockheim, 1968), New Hampshire (Harries, 1965), and New York (Witty, 1968), and several short papers appeared in the peer-reviewed literature in the latter half of the 20th century (e.g., Bliss and Woodwell, 1965; Bockheim and Struchtemeyer, 1969; Witty and Arnold, 1970). One commonality among these studies is the conclusion that pedogenesis in these environments involves bedrock weathering. This interpretation was updated and explored in more detail for alpine zones in Vermont by Munroe et al. (2007) and Munroe (2008). It is notable, however, that this previous work did not specifically investigate the possibility that alpine soils in the northeastern Appalachians may have developed in surficial sediments deposited by the Laurentide Ice Sheet, which is known to have inundated the region completely (Goldthwait, 1970). This oversight may reflect the fact that slope processes removed glacial sediments from much of the steeply sloping topography at higher elevations during the glacial-postglacial transition. However, in places where glacial sediments persist, they could mask the underlying bedrock to such an extent that bedrock weathering makes no contribution to pedogenesis.

The purpose of this study was to investigate pedogenesis and evaluate the relative importance of surficial sediments and bedrock as parent materials for alpine soils in part of the White Mountains of New Hampshire. The study area was selected because recently published bedrock mapping (Eusden, 2010) reveals strongly contrasting rock types beneath a thin layer of glacial till (Borns et al., 1987) locally reworked by post-glacial colluvial activity (Fowler, 2010). Previous work in this area (Harries, 1965) proposed that properties of the underlying bedrock control characteristics of the overlying soil; however, it is unclear if this is possible through a laterally continuous mantle of surficial sediment. Accordingly, the primary objective was

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to examine alpine soils developed over contrasting bedrock types to determine if they differ in significant ways. The guiding hypothesis was that alpine soils in the study area should be similar, despite the differences in their underlying bedrock, because they have developed in a homogenous layer of glacial sediment.

Study Area

SETTING

The study area for this project is in the Presidential Range of the White Mountains in New Hampshire, U.S.A. The Presidential Range extends for ~20 km along a southwest to northeast axis in the central White Mountains (Fig. 1). The highest summit in the northern Appalachians, Mount Washington (1917 m), is located roughly in the center of the Presidential Range, and is surrounded by the most extensive (~11.3 km^2) alpine zone in the northeastern United States (Kimball and Weihrauch, 2000). Alpine treeline in the Presidential Range is at an elevation of approximately 1500 m (Kimball and Weihrauch, 2000).

Approximately 1.5 km to the southwest of Mount Washington is Mount Monroe (1637 m), the fourth highest summit in New Hampshire (Fig. 1). Wrapping from north to east around Mount Monroe are the Monroe Flats (~1550 m), an expanse of relatively gently sloping topography near the Lakes of the Clouds, the highest permanent water bodies in the region. The Appalachian Trail passes through this area as the Crawford Path, carrying significant foot traffic. The Monroe Flats are known for a diverse array of alpine plants, including endemic *P. robbinsiana*.

CLIMATE

The weather on Mount Washington is extreme, as documented by the Mount Washington Observatory, which has operated continuously since 1932 (http://www.mountwashington.org). The observatory (at 1917 m) claims the highest surface wind speed observed in the northern hemisphere, 103 m s^{-1}, recorded in April 1934. The annual average wind speed is 15 m s^{-1}, and the summit receives an average of ~2500 mm of precipitation each year. The majority of this falls as snow, with an annual mean of ~7 m. The mean annual temperature at the summit is –2.6 °C, with July averaging 9.5 °C and January averaging –15.2 °C. Conditions on the Monroe Flats, at an elevation ~350 m below the summit observatory, are presumably less severe, but are nonetheless cold, windy, and wet.

BEDROCK GEOLOGY

The Presidential Range has its origins in the Acadian Orogeny, as marine sediments were caught between the colliding continental Avalon plate and the oceanic Laurentia plate (Eusden, 2010).

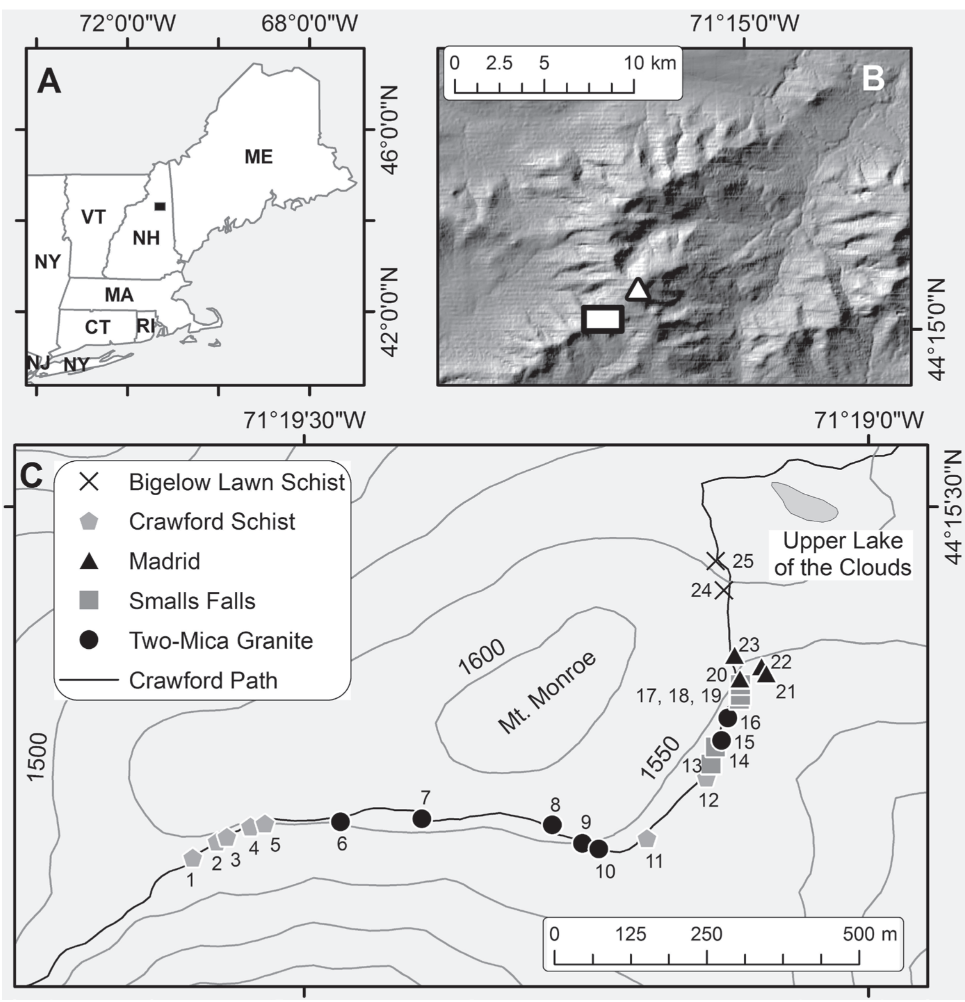

FIGURE 1. (A) Location of the White Mountains in the northeastern U.S.A. NH: New Hampshire, ME: Maine, VT: Vermont, NY: New York, MA: Massachusetts, RI: Rhode Island, CT: Connecticut. Black box outlines area shown in part B. (B) Hillshaded elevation model of the Presidential Range in New Hampshire. Mount Washington is noted by the triangle. Area shown in part C is highlighted by the white box. (C) Location of the Monroe Flats study area along the south and east side of Mount Monroe. Soil sampling sites are identified by number linked to Table 1. Symbols represent the five bedrock types mapped beneath the study area.

Several rock types, ranging in age from Silurian to Devonian, are present in the study area:

CRAWFORD MEMBER OF THE RANGELEY FORMATION

This Silurian-age migmatitic gneiss displays alternating layers of quartz with feldspar and black biotite-rich schist. In some areas the gneiss is extensively injected by two-mica pegmatites, aplites, and granites (Eusden, 2010).

SMALLS FALLS FORMATION

This well-foliated Silurian schist is distinctly rusty brown when weathered. It includes muscovite, biotite, quartz, plagioclase, chlorite, sillimanite, graphite, pyrrhotite, and ilmenite with a total thickness of 10–50 m (Eusden, 2010; Eusden et al., 1996). Sediments of this formation were deposited in an anoxic ocean basin. Its rusty-brown color results from the weathering of iron-bearing sulfide minerals that formed in reducing environments (Eusden et al., 2013).

MADRID FORMATION

This fine-grained Silurian rock consists of thinly laminated granofels with alternating layers of biotite-rich, schistose granofels and green to purple, calc-silicate granofels. It includes actinolite, quartz, biotite, plagioclase, sphene, and garnet, with trace amounts of chlorite and epidote and is 10–50 m thick (Eusden, 2010; Eusden et al., 1996). The Madrid Formation marks a shift in depositional environment from the anoxic basin of the Smalls Falls Formation to a well-oxygenated marine setting. It likely received sediment from the neighboring reef of the Fitch Formation, which provided a source of carbonate for formation of calc-silicate minerals (Eusden et al., 2013).

BIGELOW LAWN MEMBER OF THE LITTLETON FORMATION

This Devonian schist is composed primarily of quartz, muscovite, and biotite. The rock appears massive with randomly spaced, thin quartzite layers making up 5%–10% of the unit (Eusden, 2010). The formation contains some of the youngest metasedimentary rocks in the White Mountains, originally deep-water muds and sands (Eusden et al., 2013).

TWO-MICA GRANITE

The medium- to coarse-grained Two-Mica Granite is early Devonian in age and includes aplite and pegmatite (Eusden, 2010). This granite intruded into the Littleton Formation during a phase of magmatism linked to the Acadian Orogeny (Eusden et al., 2013).

SURFICIAL GEOLOGY AND SOILS

The surficial geology of the Monroe Flats has been studied extensively because of the location's relative accessibility and proximity to Mount Washington. The area was covered entirely by continental ice at the peak of the Wisconsin Glaciation, ca. 20,000 years ago (Goldthwait, 1939; Thompson, 1999). Bedrock surfaces exhibit glacial striations and asymmetric erosional features recording overrunning of ice from the northwest to the southeast (Goldthwait, 1970; Fowler, 1971). Recently published mapping classifies the surficial deposits of the Monroe Flats as "lower-slope diamict" dating to the late Pleistocene or early Holocene (Fowler, 2010). This diamict, which features a range of lithologies and textures, is interpreted to have been formed by downslope reworking of glacial till.

Fowler (1971, 1976) described a set of periglacial turf-banked terraces located on the Monroe Flats near the Lakes of the Clouds (Fig. 1). These features, which define the landscape in 30 cm to 45 cm steps, are not common elsewhere in the Presidential Range. Fowler (1976) found the terrace soils to be composed of 60% sand, 25% channers (flat cobbles), and 15% silt and finer particles. The distinctive channery surfaces tend to be dry and barren, yet local pockets of finer-grained soil support vegetation such as *Diapensia lapponica* (diapensia) and *P. robbinsiana*. Fowler (1976) proposed that the east- and southeast-facing slopes of these terraces provide shelter from prevailing northwest winds, allowing the soils to retain moisture that aids their downslope movement. It is unclear when the terraces were last active; Fowler (1976) reports that despite 60–80 freeze-thaw cycles per year, a five-year study of the area revealed no movement or creep.

Soils in the Presidential Range alpine zone were studied by Harries (1965), who identified three distinct types. Profiles classified as "Rankers," similar to Entisols in U.S. Department of Agriculture Soil Taxonomy (Soil Survey Staff, 2014), featured thick A horizons over C horizons derived from weathering of the underlying bedrock. "Podzols" (Spodosols) exhibited more pronounced weathering and evidence for translocation of humus and iron oxides. The third category of soils, referred to as "Braunerde" (Inceptisols), featured larger fractions of sand, reddish-yellow colors, and high concentrations of iron oxides. Harries (1965) noted that Braunerde profiles were common over gneiss-granulite bedrock, whereas Rankers were abundant over mica schist and quartzite. Harries (1965) further suggested that soils derived from calc-silicate rocks such as the Madrid Formation support more diverse plant communities, but cautioned that further investigation was needed. Harries (1965) did not specifically consider whether alpine soils in the Presidential Range may have developed in glacial sediments overlying the bedrock.

Methods

FIELD METHODS

Samples were collected along the edge of the Appalachian Trail (Crawford Path) along the south, east, and northeast slopes of Mount Monroe in September 2013 (Fig. 1, Table 1). A total of 72 soil samples and 5 rock samples were taken from 25 profiles above the Madrid Formation, Smalls Falls Formation, Crawford Member, Bigelow Member, and Two-Mica Granite, as mapped by Eusden (2010). The footbed of the trail has been eroded 20–50 cm below the surface in many places, and most samples were collected directly from these trailcut exposures to minimize disruption. Sites were selected in areas of similar micro-topography, with gently sloping undisturbed surfaces. Locations were recorded with a GPS, and the depth, horizon type, surrounding vegetation, and lithology of bedrock float were recorded for each sample (Table 1). A representative sample was also taken from each of the five bedrock formations. None of the trailcut exposures was deep enough to expose unweathered glacial till, and the thickness of this material is unknown.

TABLE 1

Locations and properties of sampled soil profiles.

Name	Easting$ (m)	Northing$ (m)	Elevation (m)	Vegetation	Vegetation	Horizon	Depth (cm)	Moist color	Texture
MM-1	314257	4902623	1538	*Carex, Vaccinium, Betula*	Crawford Member (schist)	A	0–22	5YR 2.5/1	SL
						Bw	22–40	7.5YR 2.5/2	LS
MM-2*	314287	4902649	1544	*Carex, Vaccinium, Betula, Empetrum, Ledum*	Crawford Member (schist)	Oa	0–10	5YR 2.5/1	SiL
						A	10–20	10 YR 2/1	SL
						Bw	20–40	7.5 YR 2.5/2	SL
MM-3*	314298	4902656	1547	*Carex, Vaccinium, Betula,* lichens	Crawford Member (schist)	Oa	0–6	7.5 2.5/1	SL
						A	6–14	7.5 YR 3/1	SL
						Bw	14–40	7.5 YR 2.5/3	SL
						BC	40–50+	10YR 3/3	SL
MM-4	314327	4902672	1549	*Carex, Vaccinium*	Crawford Member (schist)	Oa	0–6	7.5 YR 2.5/1	SL
						A	6–12	10 YR 3/1	SL
						Bw	12–27	7.5 YR 3/4	S
						BC	27–45+	10YR 4/6	LS
MM-5	314344	4902677	1551	*Abies* krummholz	Crawford Member (schist)	A	0–10	5YR 2.5/1	SiL
						E	10–25	7.5YR 4/1	SL
						Bw	25–40	7.5YR 2.5/2	SiL
						BC	40–50	7.5YR 3/3	SL
MM-6	314433	4902677	1557	*Carex*	Two Mica Granite	Oa	0–6	10YR 2/1	SL
						A	6–20	10YR 2/2	LS
						Bw	20–40	7.5YR 3/4	LS
MM-7*	314529	4902679	1562	*Vaccinium, Carex, Ledum*	Two Mica Granite	A	0–10	7.5YR 2.5/2	SL
						Bw	10–35	10YR 2/2	LS
						BC	35–55	10YR 3/3	LS
MM-8*	314682	4902665	1558	*Vaccinium, Carex, Ledum*	Two Mica Granite	Oa	0–5	7.5YR 2.5/2	LS
						A	5–20	2.5YR 2.5/1	SL
						Bw	20–28	5YR 3/4	SL
						BC	28–45	10YR 4/6	SL
MM-9	314717	4902633	1550	*Abies krummholz, Vaccinium*	Two Mica Granite	A	0–20	10YR 2/1	SL
						Bw	20–40+	7.5YR 3/3	SL

TABLE 1
Continued

Name	Easting$ (m)	Northing$ (m)	Elevation (m)	Vegetation	Vegetation	Horizon	Depth (cm)	Moist color	Texture
MM-10	314736	4902624	1551	*Diapensia*	Crawford Member (schist)	A	0–10	10YR 2/2	LS
						Bw	10–25	7.5YR 3/3	SL
						Ab	25–30	5YR 2.5/2	LS
						Bb	30–40	5YR 3/4	LS
MM-11	314793	4902640	1549	*Diapensia*	Crawford Member (schist)	A	0–30	7.5YR 2.5/1	SL
						Bw	30–45+	10YR 3/6	LS
MM-12	314866	4902737	1543	*Diapensia*	Smalls Falls (rusty schist)	A	0–10	10YR 3/4	SL
						Bw	10+	10YR 5/8	SL
MM-13	314872	4902759	1542	*Diapensia*	Smalls Falls (rusty schist)	A	0–10	10YR 3/3	SL
						Bw	10–30+	10YR 3/6	LS
MM-14	314878	4902787	1542	*Diapensia, Carex*	Two Mica Granite	A	0–14	7.5YR 2.5/1	SL
						Bw	14–30	5YR 3/4	LS
						BC	30–45+	10YR 5/8	SL
MM-15	314886	4902797	1545	*Diapensia, Carex*	Two Mica Granite	A	0–15	7.5YR 2/2	LS
						Bw	15–30	5YR 3/4	LS
						BC	30–50+	5YR 3/4	LS
MM-16*	314894	4902834	1546	*Carex, Vaccinium*	Smalls Falls (rusty schist)	A	0–10	7.5YR 2.5/2	SL
						Bw	10–20	10YR 3/6	SL
						BC	25–45	10YR 4/6	SL
MM-17	314909	4902864	1548	*Diapensia,* some bare spots	Smalls Falls (rusty schist)	A	0–8	7.5YR 2.5/3	S
						Bw	8–70+	5YR 3/4	LS
						B2		5YR 3/4	LS
MM-18*	314910	4902871	1547	*Diapensia*	Smalls Falls (rusty schist)	A	0–10	7.5YR 2.5/3	SL
						Bw	10–30	5YR 3/4	LS
						BC	30–45+	10YR 4/6	LS
MM-19	314911	4902888	1550	*Vaccinium, Carex*	Madrid (granofels)	A	0–10	7.5YR 2.5/1	SiL
						Bw	10–35	7.5YR 4/6	SL
						BC	35–45+	10YR 4/6	SL
MM-20*	314936	4902917	1551	bare, channery	Madrid (granofels)	A	0–15	10YR 2/2	SL
						Bw	15–30+	7.5YR 3/3	SL
MM-21*	314941	4902905	1547	bare, channery	Madrid (granofels)	A	0–20	7.5YR 2.5/2	SL
						A2	20+	7.5YR 2.5/3	LS

TABLE 1
Continued

Name	Easting$ (m)	Northing$ (m)	Elevation (m)	Vegetation	Vegetation	Horizon	Depth (cm)	Moist color	Texture
MM-22*	314910	4902898	1551	*Vaccinium, Carex*	Madrid (granofels)	A	0–12	7.5YR 2.5/1	SL
						Bw	12–30	2.5YR 2.5/3	SL
						BC	30–50+	10YR 4/6	LS
MM-23	314905	4902937	1555	*Diapensia, Carex, Vaccinium, Potentilla*	Madrid (granofels)	A	0–15	7.5YR 2.5/2	SL
						Bw	15–40	5YR 3/4	LS
						BC	40–55+	5YR 3/4	LS
MM-24	314895	4903043	1553	bare	Bigelow Lawn (schist)	A	0–7	7.5YR 2.5/3	SL
						Bw	7–15	7.5YR 3/4	SL
MM-25	314887	4903091	1545	*Betula, Vaccinium, Lycopodium*	Bigelow Lawn (schist)	A	0–25	7.5YR 2.5/1	SL
						Bw	25–50	10YR 3/6	LS
						BC	50–60+	10YR 4/6	SL

$UTM zone 19N, NAD-83.
*Included in sample subset for geochemical and mineralogical analysis.

LABORATORY ANALYSIS

Soil samples were subjected to a variety of analyses in the laboratory. Because of harsh conditions in the field, moist Munsell color was determined immediately upon return to the laboratory under natural sunlight. Soil particle density (Bielders et al., 1990) was determined using a Quantachrome Pentapyc 5200e, which measures the volumes of irregularly shaped solids through nitrogen displacement. Organic matter by loss on ignition (Dean, 1974) was determined using a Leco TGA701 thermogravimetric analyzer. Soils were heated to 105 °C for 4 h to determine percent moisture, and 550 °C for 3 h to determine percent organic matter. The ratio of carbon to nitrogen was measured for freeze-dried and ground samples of Oa and A horizons with a Thermo Flash 2000 Elemental Analyzer. Grain size analysis was performed via laser scattering with a Horiba LA-950. Prior to grain size analysis, organic matter was removed with 35% H_2O_2. Samples were then centrifuged, decanted, mixed with a sodium hexametaphosphate deflocculant, and ultrasonified before analysis.

A representative subset of 24 samples from profiles with similar horizonation, thickness, and vegetation (primarily *Carex* and *Vaccinium*) was selected for chemical and mineralogical analysis (Table 1). Six samples were chosen from profiles above four different bedrock formations: Crawford Member, Two-Mica Granite, Smalls Falls, and Madrid. The Bigelow Lawn Schist was excluded because it is nearly identical to the Crawford Member. Soil pH was measured using a soil-to-deionized-water ratio of 1:2 (Thomas, 1996) and an Orion 420A+ meter calibrated with a 4 pH standard. These 1:2 pH values were then converted to a 1:1 equivalent based on the methods of Sikora and Kissel (2014).

Mineralogical composition was determined for the soil subset and four rock samples through X-ray diffraction (XRD) using a Bruker D8 analyzer with CuKα radiation and a theta-theta goniometer. In preparation, whole rock samples were crushed and powdered in a shatter box, and soils were sieved to 1.68 mm. Rock samples were analyzed as randomly oriented powders. Soil samples were mixed with distilled water, pipetted onto glass slides, and dried for 24 h at 60 °C. Both rock powders and slides were scanned from 2–70° 2θ at 3° min^{-1}.

Soil chemical properties of the 24-sample subset were determined by the University of Maine Soil Testing Service. Exchangeable acidity was determined through KCl leaching and a NaOH titration according to the methods of Fernandez (1988). Extractable cations were measured with NH_4Cl extraction and inductively coupled plasma–atomic emission spectroscopy (ICP-AES) analysis based on the methods of Fernandez (1988) and Robarge and Fernandez (1986). Estimated cation exchange capacity (eCEC) was calculated by summing the Ca, K, Mg, Na, and KCl-acidity following Fernandez (1988). Profile quantities of exchangeable cations (in kg m^{-2} per 50 cm of soil depth) were calculated on a stone-free basis from measured abundances and soil densities.

Bulk geochemistry of the 24-sample subset and four rock powders was determined through ICP-AES following ignition at 1000 °C and fluxing with $LiBO_2$. Commonly employed weathering indices (e.g., Birkeland, 1999) were calculated from the abundances of major elements.

Statistical significance was assessed using nonparametric Kruskal-Wallis test, because the sample sets are small and the data are not normally distributed. A P value of 0.05 was used as the significance threshold.

Results

SOIL PROPERTIES

Soil profiles on the Monroe Flats range from 15 cm to >70 cm thick (Table 1). Maximum profile thickness is unknown because bedrock was not reached in most locations. Each profile contains an A and Bw horizon, and Oa and BC horizons were also encountered (Table 1). An E horizon was noted in one profile (MM-5); buried A and Bw horizons were observed in another (MM-10). Oa horizons were noted only over the Crawford Member and the Two-Mica Granite, whereas profiles over the Madrid and Smalls Falls Formations are dominated by A and relatively thick Bw horizons. Moist colors range widely with hues from 2.5YR to 10YR and chromas from 1 to 8, with a median value of 3 (Table 1). Soil particle density increases downward, averaging 1.22 g cm^{-3} for Oa and A horizons, 1.89 g cm^{-3} for Bw horizons, and 2.03 g cm^{-3} for BC horizons (Table 2, Fig. 2).

Carbon-nitrogen ratios of Oa and A horizons range from 10 to 23 with a mean of ~15 (Table 2). The abundance of organic matter varies from 2.4% to 50% (Table 2, Fig. 2); however, only eight samples have values greater than 15% and the overall median is 7%.

Median grain size varies from ~40 µm to ~206 µm (overall average of 117 µm), and fine sand is the most abundant size fraction (13% to 41% of each sample, mean of 27%, Fig. 3). On average, 67% of each sample is sand, with ~33% silt and <1% clay. Sandy loam textures are most common in A (70%) and BC (54%) horizons, whereas loamy sand is most common (48%) in B horizons (Table 1). Textures of silt loam and sand were also noted, but are rare. There is a general trend toward coarser grain size with depth (Table 2). Samples from Oa and A horizons have average median grain sizes of ~105 µm, which is significantly finer than Bw and BC horizons (~125 µm, Fig. 2).

ICP analysis of major and trace elements reveals that samples are dominated by SiO_2, Al_2O_3, and Fe_2O_3 with averages of 56.7%, 15.1%, and 8.2% respectively. Barium, Zr, Sr, and V are the most abundant of the measured trace elements averaging 356 ppm, 246 ppm, 143 ppm, and 128 ppm respectively. Abundances of all major elements except P are greatest in the BC horizon, and generally decrease toward the surface (Table 3). Ratios of immobile elements Zr and Ti are essentially constant in A, Bw, and BC horizons.

Soil chemistry reveals that Al is the most abundant exchangeable cation, with a median abundance of 275 mg kg^{-1}, followed by Fe, K, and Ca with median values of 63 mg kg^{-1}, 26 mg kg^{-1}, and 20 mg kg^{-1}. Exchangeable acidity ranges from 0.6 to 10.6 $cmol_c$ kg^{-1} with a mean of 5.4 $cmol_c$ kg^{-1}, and closely correlates with estimated cation exchange capacity (eCEC). Concentrations of cations and exchangeable acidity are greater in A horizons, and lower in Bw and BC horizons (Table 3). These differences are significant for Ca, K, and Mg. The pH of these soils ranges from 2.9 to 3.3 with a mean value of 3.0 (Table 3).

TABLE 2

Physical properties grouped by horizon.

Property	Units	Statistic	Horizon: Oa	A	Bw	BC
Organic Matter	%	Max	50.0	30.8	18.9	10.0
		Median	19.1	11.1	5.9	5.1
		Min	6.3	4.1	2.7	2.4
C:N*	—	Max	19.0	23.1	—	—
		Median	17.4	16.3	—	—
		Min	15.0	10.7	—	—
Particle density	gm cm^{-3}	Max	1.8	2.4	2.5	2.6
		Median	1.0	1.4	1.8	1.9
		Min	0.5	0.7	1.2	1.5
Median grain size	µm	Max	165.6	192.9	206.4	170.0
		Median	100.2	106.0	125.0	128.5
		Min	60.1	39.9	54.2	64.6
Sand	%	Max	77.2	87.7	89.2	80.0
		Median	66.7	64.4	71.0	68.3
		Min	48.9	39.3	44.9	50.7
Silt	%	Max	50.3	59.6	54.0	45.7
		Median	33.3	35.5	28.9	30.9
		Min	22.8	12.3	10.8	19.6
Clay	%	Max	0.8	1.2	1.2	2.0
		Median	0.0	0.2	0.0	0.2
		Min	0.0	0.0	0.0	0.0

*Only calculated for Oa and A horizons

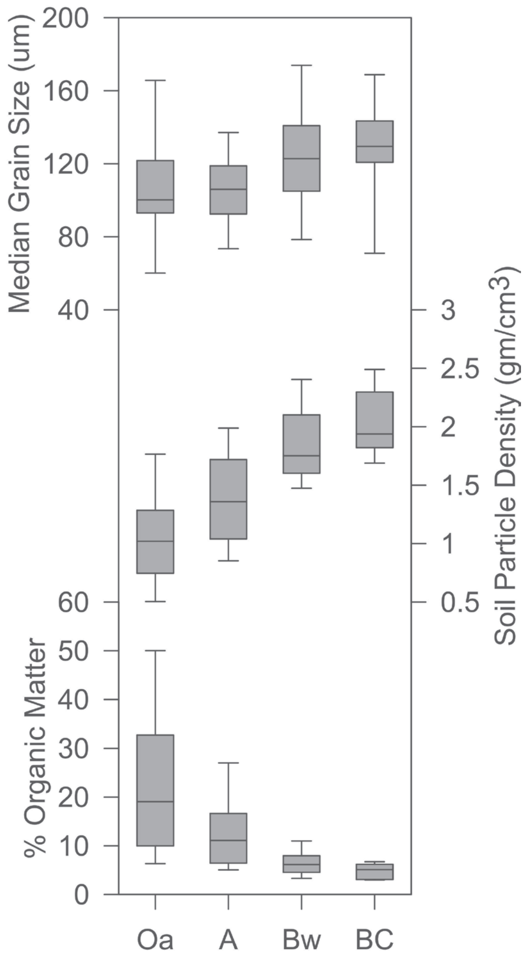

FIGURE 2. Boxplot of selected results by soil horizon. Abundance of organic matter, soil particle density, and median grain size all exhibit significantly different average values between horizons when evaluated with a Kruskal-Wallis test.

X-ray diffraction (XRD) reveals the presence of quartz, mica, and plagioclase in all rock samples. These three minerals, along with chlorite and hydrobiotite (interstratified biotite-vermiculite), are also present in nearly all soil samples (Fig. 4).

Direct measurement of the mean annual soil temperature (MAST) of these soils was not conducted; however, preliminary data from a similar elevation (1615 m) nearby reveal a MAST of ~2.5 °C (http://www.mountwashington.org). Accordingly, the profiles in this study are considered to have a cryic thermal regime. Most profiles classify as Typic Dystrocrypets, although five have umbric epipedons and classify as Typic Humicryepts (Soil Survey Staff, 2014).

RESULTS BY BEDROCK FORMATION

Laboratory results reveal that soils over the four bedrock formations are notably similar; median grain size is the only measured soil property exhibiting significant differences over contrasting bedrock types. The average median grain size is largest (~128 µm) for soils over the Smalls Falls Formation and Two-Mica Granite, and smallest (103 µm) for soils over the Crawford Member. However, all other measured properties are statistically indistinguishable in soil profiles above the four bedrock formations (Table 4).

Geochemical analysis demonstrates notable differences in the bulk elemental composition of the four rock types (Fig. 5). The abundances of SiO_2 (77.5%) and Na_2O (1.8%) are highest in the Two-Mica Granite. The Crawford Schist contains the greatest abundance of Fe_2O_3 (8.0%) and K_2O (5.3%). TiO_2 (1.1%) and Al_2O_3 (19.4%) are most abundant in the Smalls Falls Formation, and MgO (3.2%) and CaO (5.2%) occur at the highest levels in the Madrid Formation (Fig. 5). Similar contrasts are observed in the abundances of trace elements (Table 5).

Overall, however, these differences in rock geochemistry are not mirrored by bulk soil geochemistry. For instance, SiO_2 is low, and Fe_2O_3 is high, in soils over the Two-Mica Granite, directly opposing their abundances in the bedrock (Fig. 5). Similarly, the

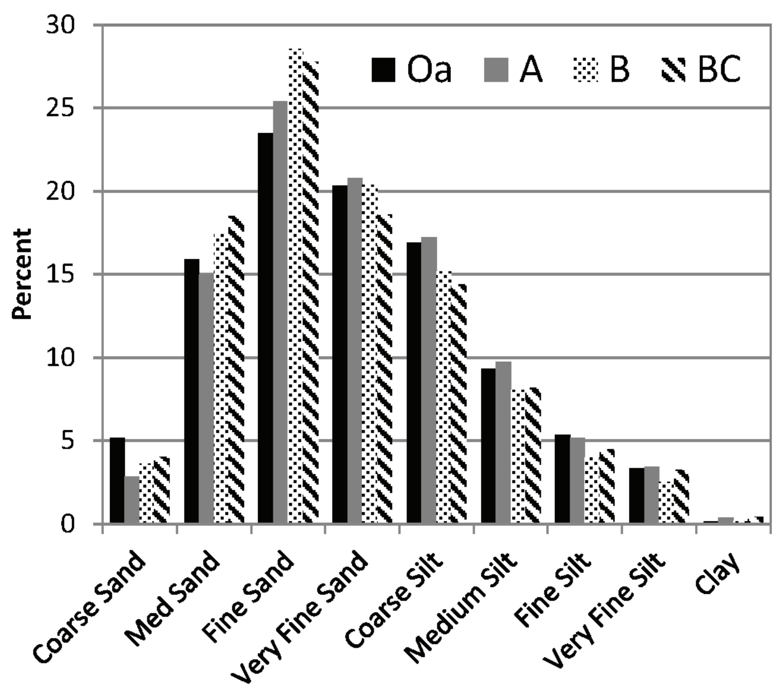

FIGURE 3. Grain size distribution of different soil horizons. All horizons have a similar distribution, dominated by fine and very fine sand. Measured abundance of clay (<2 µm) is <1%.

TABLE 3

Geochemical results grouped by horizon.

Element	Units	Horizon			
		Oa	A	Bw	BC
SiO_2	%	39.0	53.2	51.0	53.8
TiO_2	%	0.6	0.9	0.8	1.0
Al_2O_3	%	8.3	13.7	14.5	15.5
Fe_2O_3	%	2.6	6.5	7.3	9.4
MnO	%	0.1	0.1	0.1	0.1
MgO	%	0.4	1.0	1.5	1.8
CaO	%	0.7	1.0	1.0	1.3
Na_2O	%	1.2	1.5	1.6	2.1
K_2O	%	1.5	2.5	2.0	2.4
P_2O_5	%	0.4	0.3	0.3	0.3
Ba	ppm	277.0	388.0	373.0	382.0
Co	ppm	<1.0	3.1	2.5	1.8
Cr	ppm	30.8	67.8	71.3	78.1
Cu	ppm	15.9	23.6	26.9	35.2
Ni	ppm	13.8	22.9	22.2	21.7
Pb	ppm	8.3	8.5	6.9	7.4
Sc	ppm	<1.0	5.0	3.8	4.7
Sr	ppm	80.0	124.0	121.0	175.0
V	ppm	71.5	131.0	120.5	142.0
Y	ppm	19.6	16.2	16.6	21.7
Zn	ppm	117.0	85.7	93.4	104.9
Zr	ppm	235.0	264.0	266.5	262.5
pH	—	3.2	2.9	3.0	3.0
exch. Ca	mg kg^{-1}	104.6	19.9	15.7	12.8
exch. K	mg kg^{-1}	182.2	22.3	6.8	6.7
exch. Mg	mg kg^{-1}	88.6	9.6	3.2	2.0
exch. Al	mg kg^{-1}	645.8	345.0	272.3	167.5
exch. Fe	mg kg^{-1}	196.8	72.0	54.5	22.6
exch. Mn	mg kg^{-1}	2.1	0.5	0.4	0.4
exch. Na	mg kg^{-1}	6.7	3.5	2.2	2.3
exch. Zn	mg kg^{-1}	2.8	0.4	0.1	0.1
exch. acidity	cmol$_c$ kg^{-1}	10.6	7.0	5.6	3.6
eCEC	cmol$_c$ kg^{-1}	12.3	7.6	5.7	3.7

abundance of trace elements follows nearly identical patterns in the soils over the four rock types (Fig. 6). The elements Sr, V, Zn, and Zr exhibit some variability, but the concentrations of Ba, Co, Cr, Cu, Ni, Pb, Sc, and Y are nearly indistinguishable between soils over the different bedrock formations (Table 5).

Evaluating differences in profile quantities of exchangeable cations in soils over different bedrock formations is hampered by the small number of horizons analyzed; however, a few trends are notable (Table 5). Profile quantities of Ca (per 50 cm of soil depth) are consistent over all four rock types, averaging 13.0 gm m^{-2}. Profile quantities of Mg and Al are highest over the Crawford Member, and lowest over the Madrid. Quantities of Na exhibit the opposite pattern. No consistent correlation between profile quantities and composition of the underlying bedrock is apparent. For instance, the bulk abundance of Ca is ~10× higher in the Madrid Formation compared with the other three rock types, but the profile quantity of Ca in soils over the Madrid is the same as in soils elsewhere in the study area.

Finally, XRD analysis reveals that soil profiles contain quartz, mica, plagioclase, and hydrobiotite regardless of underlying bedrock type (Fig. 4). Chlorite is also detectable in all soil profiles, but is only found in rock samples of the Crawford Member Schist and the Smalls Falls Formation.

Discussion

PEDOGENIC PROCESSES AND EVIDENCE OF WEATHERING

Field observations and laboratory analyses indicate that the alpine soils on Monroe Flats are forming primarily through accumulation of organic matter, and chemical weathering leading to leaching of mobile elements. Organic matter accumulation (paludification) is encouraged by the cold, wet climate at this elevation (~1550 m). As a result, these soils are characterized by high concentrations of organic matter (Fig. 2) in Oa and A horizons (up to 50%), in contrast to Bw (4%–30%) and BC horizons (2%–10%). Nevertheless, these values are lower than the concentrations of organic matter reported for soils on Mount Mansfield in Vermont (Munroe, 2008) and at other locations in the Presidential Range (Harries, 1965), which reached 90%. Unlike the Mount Mansfield soils, however, the presence or absence of an Oa horizon in the Monroe Flats study area does not correlate with thickness of the soil profile. Total profile thicknesses in this study range up to 70 cm, whereas profiles with Oa horizons are 40–50 cm thick.

Other properties of the studied soils provide evidence for in situ weathering. Munsell values and chromas are significantly higher in Bw and BC horizons compared to A horizons (Table 1). In part this is a reflection of paludification darkening the surface horizons. However, the strong increase in chroma with depth stems from iron oxidation that produces relatively bright red and orange colors.

Soil chemical analyses also illustrate the effects of weathering. Calculation of weathering indices (e.g., Birkeland, 1999; Munroe et al., 2007) relating the abundance of leachable bases to stable oxides reveals a trend of increasing weathering from BC to B to A horizons in profiles over all four bedrock formations. For instance, average values for the ratio ($CaO + MgO + Na_2O$)/TiO_2 (Chittleborough, 1991) decrease from 8.3 (BC) to 8.1 (B) to 6.7 (A). Similarly, average values for the ratio ($K_2O + Na_2O + CaO + MgO$)/Al_2O_3 (Birkeland, 1999) are 0.84 in BC horizons compared with 0.78 in B and A horizons. Thus, mobile elements are being leached from horizons closer to the soil surface. Increases in the abundance of the immobile trace element Zr upward through these soil profiles supports this interpretation. Trends are less consistent in weathering indices calculated with SiO_2 in the numerator, indicating that silica is not rapidly leached in this environment.

XRD results provide additional evidence of chemical weathering as hydrobiotite, a secondary clay mineral derived from biotite, is detectable in most soil profiles. Hydrobiotite formation has been noted in climatically similar Arctic environments (e.g., Anderson et al., 2000), as well as in alpine soils on Mount Mansfield,

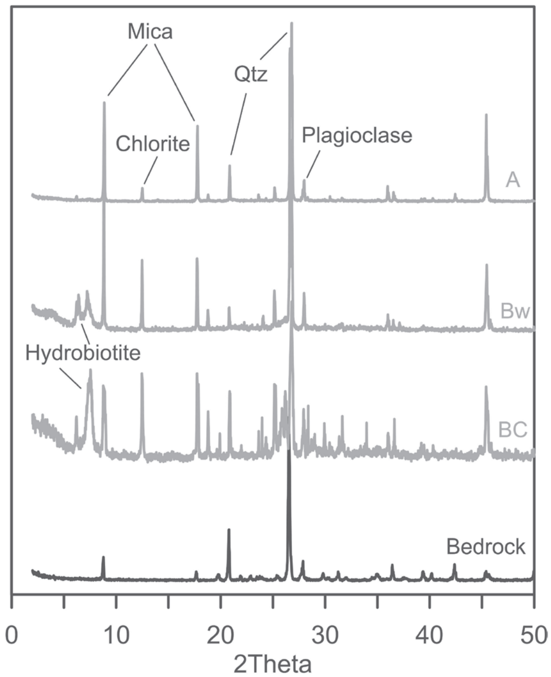

FIGURE 4. X-ray diffraction results for a representative soil profile over Two-Mica Granite. All soil horizons contain quartz, plagioclase, mica, and chlorite. Hydrobiotite is also present in the Bw and BC horizons. In contrast, chlorite is absent in the underlying bedrock, indicating that this soil is not forming in weathering bedrock, but rather in a chlorite-bearing surficial deposit, likely of glacial origin.

Vermont (Munroe et al., 2007), and can form over Holocene time scales in rapidly weathering glacial sediments (Mellor, 1986).

IDENTITY OF THE SOIL PARENT MATERIAL

Although the data collected for this project provide strong evidence that chemical weathering is involved in the formation of the alpine soils on the Monroe Flats, the physical, chemical, and mineralogical properties of these soils are notably decoupled from the underlying bedrock. A few soil properties do exhibit significant differences over different bedrock formations, for instance median grain size and the abundance of some major and trace elements. Overall, however, the soil profiles are strikingly similar to one another regardless of which strongly contrasting bedrock type is located beneath them. This situation supports the hypothesis that these soils are not forming directly in weathering bedrock, but rather in a homogenized layer of surficial sediment containing a blend of the underlying rock types. The strongest evidence in support of this interpretation is the lack of significant differences in most soil properties between profiles over different rock types, the similarity of trace element concentrations in all soil profiles, and the ubiquity of detrital chlorite in soil samples despite the absence of this mineral in two of the four bedrock formations (Two-Mica Granite and Madrid Formation).

The most likely identity of this parent material is glacial sediment deposited during the waning stages of the Wisconsin Glaciation. Erosion and transport of rock fragments derived from local bedrock would deposit till containing a mixture of nearby bedrock formations. The chlorite-bearing Crawford Member, in particular, may have contributed heavily to the composition of this till because it is the most extensive formation in the study area, as well as in areas downslope to the northwest, the direction from which the ice was flowing (Fowler, 1971). Diamicton interpreted as glacial till has been reported from excavations at Lakes of the Clouds to the west of the study area (Fowler, 1979), as well as from the summit of Mount Washington, ~1.5 km to the north and ~350 m higher in elevation (Goldthwait, 1939). In light of these observations, the entire area has been mapped as “attenuated drift” on the regional Quaternary geologic map (Borns et al., 1987).

Another possibility is that these soils are developing in a postglacial colluvial deposit. Fowler (2010) subscribed to this interpretation in mapping the deposits of the Monroe Flats as lower slope diamict with provenance from slopes above. Certainly mass wasting and soil creep have impacted the soils of the study area. The turf-banked terraces are geomorphic evidence of periglacial slope processes, as are the buried A and Bw horizons at site MM-10 (Table 1). However, all soil profiles sampled for this project are located downslope from the Two-Mica Granite, which forms the summit of Mount Monroe (Eusden, 2010). This rock type lacks chlorite (Fig. 4), thus downslope movement of sediment derived from the granite cannot explain the presence of chlorite in the soil profiles. If colluvial activity is responsible for the parent material of soils in the study area, slope processes must be remobilizing previously deposited glacial till, redistributing this chlorite-bearing sediment across the landscape as a uniform parent material in which soils can form in the absence of direct influence from the underlying bedrock. Thus, glacial till is the ultimate identity of the soil parent material in either scenario. Determining conclusively whether or not the soil parent material was redeposited by slope processes before undergoing pedogenesis is not possible with the observations made in this study. However, the high soil particle densities noted for BC horizons (>2 gm cm^{-3}) seem consistent with a basal till parent material (Table 2, Fig. 2).

IMPLICATIONS

Given the evidence presented here, it is clear that soils on the Monroe Flats are forming in unconsolidated surficial sediments. A review of the literature reveals, however, that this situation is unique within the region. For instance, Bliss and Woodwell (1965) and Bockheim and Struchtemeyer (1969) described podzols forming in weathering granitic bedrock on alpine summits in Maine. Similarly, Munroe et al. (2007) documented evidence of chemical weathering of schist bedrock as a contribution to soil formation on Mount Mansfield in Vermont. No evidence of a glacial parent material was noted in that study. In New York, Witty and Arnold (1970) reported that mineral material at the base of alpine soil profiles in the Adirondack Mountains is derived from weathering of local anorthosite. Most notably, Harries (1965) concluded that bedrock was the parent material for the alpine soils in the Presidential Range and proposed that contrasts in bedrock type controlled the distribution of Ranker, Podzol, and Braunerde profiles.

A likely explanation for this discrepancy is that the gently sloping nature of the Monroe Flats promoted the persistence of glacial sediment during the deglacial transition. Evidence indicates that deglaciation in this region proceeded through lowering of the ice sheet surface, with the high summits appearing as nunataks above ice in the surrounding valleys (Goldthwait and Mickelson, 1982). Although local pockets of glacial till have been reported even from the summit of Mount Washington (Goldthwait, 1939), glacial sediments on steep mountain slopes would generally have been vulnerable to

TABLE 4

Physical properties grouped by bedrock type.

Property	Units	Statistic	Bedrock Formation: Crawford Member	Two-Mica Granite	Smalls Falls	Madrid
Organic Matter	%	Max	50.0	32.7	11.1	30.8
		Median	7.2	10.0	5.5	6.7
		Min	2.4	3.0	2.7	3.1
C:N*	—	Max	19.0	19.9	15.3	17.1
		Median	17.6	18.2	13.9	12.3
		Min	17.4	16.5	12.4	10.0
Particle Density	gm cm^{-3}	Max	2.4	2.4	2.6	2.5
		Median	1.7	1.6	1.8	1.8
		Min	0.5	0.7	1.0	0.8
Median Grain Size	μm	Max	206.4	182.1	192.9	170.0
		Median	102.9	127.5	129.4	105.4
		Min	46.7	93.2	73.5	39.9
Sand	%	Max	89.2	82.6	87.7	80.0
		Median	65.8	71.0	70.0	65.6
		Min	43.3	57.6	55.3	39.3
Silt	%	Max	55.6	41.6	43.9	59.6
		Median	34.2	29.0	30.0	34.4
		Min	10.8	17.4	12.3	19.6
Clay	%	Max	1.1	0.7	0.9	2.0
		Median	0.1	0.0	0.0	0.6
		Min	0.0	0.0	0.0	0.0

*Only calculated for Oa and A horizons.

removal by slope processes during this nunatak phase, whereas deposits on the Monroe Flats could have survived to serve as soil parent materials in the Holocene. Harries (1965) did not describe soils from the Monroe Flats, and it is conceivable that glacial sediment had been removed from the areas he studied, leaving local bedrock to serve as the soil parent material. On the other hand, the Ranker and Braunderde profiles he described strongly resemble the Monroe Flats soils, raising the possibility that other soil-forming factors such as climate and vegetation drive the formation of similar soil profiles in this environment regardless of the initial parent material.

Previous work on paleobotany of the alpine zone in the Presidential Range (Miller and Spear, 1999) utilized evidence in sediment cores obtained from the Lakes of the Clouds near the Monroe Flats (Fig. 1). Evidence from these cores reveals that, in contrast to sites at lower elevation, the late-glacial flora of the alpine zone lacked calcicolous species. Macrofossils and pollen of calcicoles are absent, and moss fossils are dominantly from species tolerant of acidic conditions, despite the presence of Ca-bearing Madrid Formation bedrock in the Lakes of the Clouds watershed (Eusden, 2010). This situation is consistent with a post-glacial landscape mantled by glacial till derived from a mixture of rock types. Influence of the Madrid Formation on the properties of such till would be minimal given the limited spatial extent of this rock unit, and rapid weathering of permeable till may have quickly leached any available Ca from the surficial materials.

LIMITATIONS AND DIRECTIONS FOR FUTURE WORK

The data collected for this project update the seminal work of Harries (1965) on the pedology of alpine soils in the Presidential Range, and reveal that deposits of glacial origin masking the bedrock function as soil parent materials in some northern Appalachian alpine environments. The main limitations of this study are the relatively small number of soil samples collected from above each rock type and the unknown depth to the bedrock surface. Collection of additional samples would allow further testing of the conclusion that bedrock is not controlling soil properties in this location. Mapping of depth to bedrock with ground penetrating radar could also aid in the selection of sampling sites by identifying locations in which the bedrock is relatively shallow to compare with those in which the overlying sediments are thick. Finally, these same rock types are also present at the surface in other parts of the Presidential Range alpine zone, where glacial deposits may be thinner or absent. Soil profiles could be investigated in these areas, some of

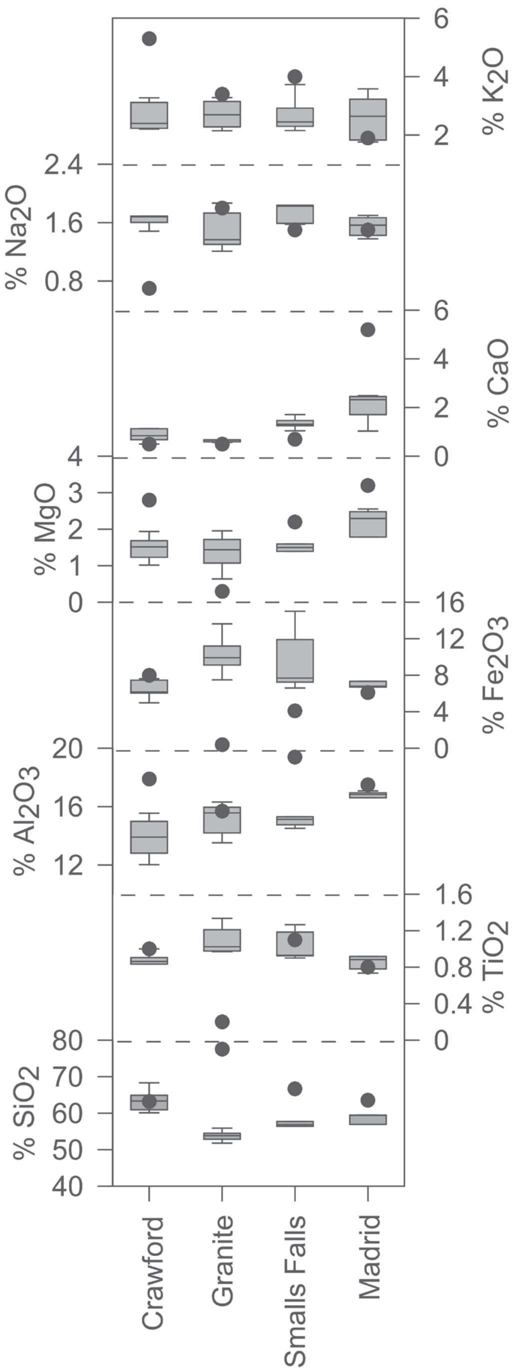

FIGURE 5. Boxplots of major elements abundances in soils over four contrasting bedrock types in the study area. Black dots mark the abundance of each element in the bedrock. There is no consistent correlation between elemental abundances in rock and overlying soil.

TABLE 5

Geochemical results grouped by bedrock type.

		Bedrock Formation			
Element	Units	Crawford Member	Two-Mica Granite	Smalls Falls	Madrid
SiO_2	%	54.5	48.5	53.2	57.0
TiO_2	%	0.8	1.0	1.0	0.9
Al_2O_3	%	11.7	14.6	14.2	16.0
Fe_2O_3	%	5.5	9.6	7.9	6.6
MnO	%	0.0	0.1	0.1	0.1
MgO	%	1.2	1.5	1.4	1.9
CaO	%	0.7	0.6	1.3	2.3
Na_2O	%	1.4	1.5	1.8	1.6
K_2O	%	2.0	2.5	2.2	2.3
P_2O_5	%	0.4	0.3	0.3	0.3
Ba	ppm	383.0	386.5	367.5	397.5
Co	ppm	4.8	2.9	1.4	3.8
Cr	ppm	57.9	69.4	69.8	77.5
Cu	ppm	26.2	36.5	21.2	31.7
Ni	ppm	26.3	21.0	14.0	22.9
Pb	ppm	7.4	7.8	4.5	5.6
Sc	ppm	3.0	3.9	5.2	5.4
Sr	ppm	110.5	97.7	169.5	222.0
V	ppm	110.5	143.0	138.0	127.0
Y	ppm	23.0	20.7	19.9	15.3
Zn	ppm	136.0	84.9	64.2	98.2
Zr	ppm	288.5	281.5	248.0	224.0
pH	—	3.0	3.0	3.0	3.2
exch. Ca	gm m^{-2}	13.0	12.9	12.7	13.2
exch. K	gm m^{-2}	13.1	14.4	13.4	6.5
exch. Mg	gm m^{-2}	6.3	4.3	4.2	2.7
exch. Al	gm m^{-2}	222.1	212.6	174.7	129.4
exch. Fe	gm m^{-2}	50.6	53.9	25.3	19.2
exch. Mn	gm m^{-2}	0.4	0.6	—	—
exch. Na	gm m^{-2}	1.7	2.0	2.1	2.4
exch. Zn	gm m^{-2}	—	—	—	—
exch. acidity	gm m^{-2}	4.5	4.6	3.4	2.5
eCEC	gm m^{-2}	4.7	4.7	3.5	2.6

which were studied by Harries (1965), to more directly assess the possible contribution of bedrock weathering to soil properties.

Conclusion

This study reveals that alpine soils on the Monroe Flats in the Presidential Range of New Hampshire are forming through organic matter accumulation and leaching of mobile elements. Both processes are aided by the cold, wet climate at this location. Typic Dystrocryepts are the most common soil type (80%), although five profiles contain umbric epipedons and classify as Typic Humicryepts. One profile beneath krummholz contained an obvious eluvial horizon, supporting reports of podsolization in alpine zones elsewhere in the northern Appalachians (e.g., Bliss and Woodwell, 1965; Harries, 1965; Bockheim and Struchtemeyer, 1969).

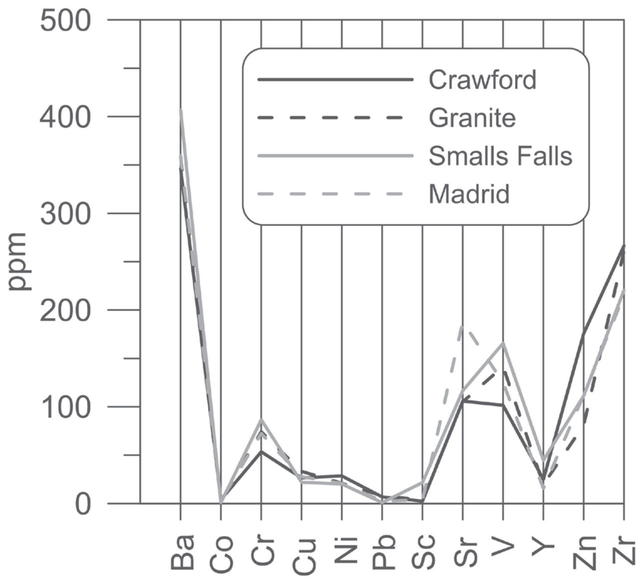

FIGURE 6. Spider diagram showing mean abundances of measured trace elements in the soils overlying the four bedrock types in the study area. The trace element patterns are notably similar for all soils and show no consistent relationship with underlying bedrock.

Results of field and laboratory investigations support the hypothesis that a homogenized layer of glacial sediment serves as the soil parent material at this location. This result stands in contrast to other alpine zones in the region where soils are forming through in situ bedrock weathering. Preservation of glacial sediment on the Monroe Flats during deglaciation may have been aided by relatively gentle slopes that reduced the efficacy of mass wasting.

A notable finding of this study is that the soils beneath the largest remnant patch of endemic *P. robbinsiana*, which is located above the Madrid Formation, are not significantly different from soils in the surrounding area. This result contradicts previous work suggesting that weathering of the Ca-rich Madrid granofels yields a soil rich in available nutrients (Harries, 1965) and supports the theory that the distribution of *P. robbinsianna* depends on a stony surface susceptible to freeze-thaw cycles that reduces competition by excluding other plants (Cogbill, 1987).

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