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Soil development along an elevational gradient in the southeastern Uinta Mountains, Utah, USA

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Abstract

A silt mantle enriched in Ca is important in buffering soils on quartzitic terrane in the southeastern Uinta Mountains. We examined 32 pedons along an elevational gradient on the south slope of the eastern Uintas to determine the amount of the silt and its importance to pedogenesis. The pedons were in the upper montane forest (2700–3000 m), subalpine forest (3000–3400 m) and alpine tundra (3400–3850 m) on stable sites. There were no significant differences in silt cap thickness or in profile quantities of silt (upper 100 cm) by ecoclimatic zone. Similar soils were found in all three ecoclimatic zones, including Eutrocryepts, Dystrocryepts, Haplocryalfs, Cryorthents, and Haplocryolls, in descending order of abundance. Profile quantities of clay, exchangeable cations, and extractable Al and solum thickness are greatest in the alpine zone, probably because the soils there are older than those at lower elevations and soil formation proceeds more rapidly. Base cycling is enhanced in alpine communities dominated by *Acomastylis* (*Geum*) *rossii* as evidenced by large profile quantities and high tissue concentrations of Ca. Profile quantities of total N and organic C are significantly greater ($p \leq 0.05$) in the alpine zone, reflecting greater below-ground production and lower rates of organic matter turnover than in soils at lower elevations.

Keywords: Silt; Pedogenesis; Calcium ion; Alpine environment; Subalpine environment

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1. Introduction

Beginning in the 1930s, there was considerable interest in altitudinal zonation of plants and soils in the western United States with regard to emerging concepts of plant ecology and factors of soil formation (Thorp, 1931; Jenny, 1941; Daubenmire, 1943; Martin and Fletcher, 1943; Whittaker et al., 1968; Hanawalt and Whittaker, 1977; Mahaney, 1978). These studies documented the effects of differences in climate along an elevational gradient, generally a decrease in temperature and an increase in precipitation, on plant communities and soil taxa. Common trends reported in these studies included increases in soil organic matter, total N, C:N ratio, soil acidity and cation-exchange capacity and a decrease in base saturation with an increase in elevation. The mechanisms for and implications of these changes are only recently becoming understood, largely through concern over anthropogenic effects on alpine and subalpine ecosystems. For example, acidic deposition may be enhancing acidification of soils in the Wind River Mountains of Wyoming (Clayton et al., 1991) and may be contributing to excess N accumulation (''N saturation'') in alpine ecosystems of the western USA (Baron et al., 1994; Williams et al., 1995; Bowman and Steltzer, 1998). In addition, air pollution may be affecting the distribution and growth of alpine plants (Bonde et al., 1982).

Bockheim and Koerner (1997) suggested that calcareous silt possibly of eolian origin was important in buffering alpine soils derived from quartzitic residuum, colluvium and till in the eastern Uinta Mountains. Other studies have recognized the importance of silt accumulation in alpine soils of the western United States (Thorn and Darmody, 1980; Birkeland et al., 1987; Litaor, 1987; Munn and Spackman, 1990; Dahms, 1993; Dahms and Rawlins, 1996).

We sampled replicate profiles in dominant vegetational communities and landforms in the alpine, subalpine, and upper montane ecoclimatic zones of the Uinta Mountains. The primary objective of the study was to determine the distribution and thickness of the silt mantle and its effect on soil development along an elevational gradient.

2. Study area

The glaciated landscape of the eastern Uinta Mountains consists of numerous compound cirques leading to deeply eroded glacial troughs, each of which is currently drained by major tributaries of the Green River. The study area for this project included three drainage basins along the south slope of the eastern Uintas within the Ashley National Forest. These were the headwaters of the Shale Creek–Uinta River drainage (Fox Lake Basin), the Whiterocks River drainage (Chepeta Basin) and the south fork of Ashley Creek (Lakeshore Basin) drainage (Fig. 1).

The study area encompassed three ecoclimatic zones (climax regions of Marr, 1967), including the upper montane forest region, the subalpine forest region, and the alpine tundra region. Along the south slope of the eastern Uinta Mountains, the upper montane forest extends from 2700 to 3000 m, the subalpine forest from 3000 to 3400 m, and the alpine tundra from 3400 to 4099 m (Lewis, 1970; Goodrich and Neese, 1986). The

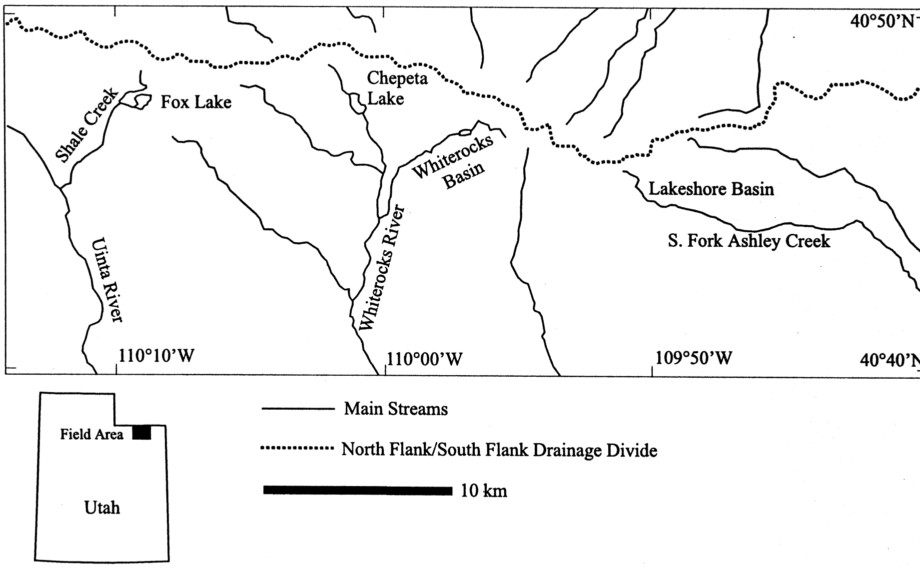

Fig. 1. Location of study areas in the Uinta Mountains of northeastern Utah.

upper montane forest contains several stand-types but lodgepole pine (*Pinus contorta*) is dominant. Common stand-types in the subalpine forest include spruce-fir (*Picea engelmannii–Abies lasiocarpa*), which is most abundant, followed by lodgepole pine mixed with spruce-fir, and various wet and dry subalpine meadows. Lewis (1970) identified seven plant communities in the alpine tundra of the Uintas, including (1) *Carex ruprestris* and cushion plants on the driest, most exposed ridges; (2) *Geum rossii* (currently classified as *Acomastylis rossii*)–sedge and sedge–*Geum* in boulder fields and dry meadows; (3) sedge-grass (*Kobresia myosuroides* (also *bellardii*)–*Poa* spp. or *C. elynoides–Poa* spp.) on high, stable ridges; (4) wet meadows and bogs dominated by *C. aquatilis, C. saxatilis,* or *Deschampsia caespitosa*; (5) *Deschampsia–Geum* meadows in basins and at the base of slopes; (6) alpine shrubs, primarily *Salix* spp. and *Dryas* spp., along streams and ponds; and (7) clumps of alpine krummholz, mostly *P. engelmannii*.

Weather records from the upper elevations in the central Rocky Mountains are fragmentary. Based on Snotel data collected by US Department of Agriculture's National Resource Conservation Service (unpublished), annual precipitation in the Uinta Mountains likely ranges between 730 and 1000 mm, with the greatest values at higher elevations. The majority of this precipitation falls as snow that is redistributed by winds in the alpine zone, resulting in large differences in local accumulation. Some alpine areas remain snow-free year-round, whereas cirque floors and subalpine uplands accumulate up to 10 m of snow. Perennial snowbanks and cornices are common at higher elevations and in other locations such as north-facing gullies.

Based on short-term soil temperature and climatic data from similar areas elsewhere in the central Rocky Mountains, the mean annual soil temperature at 50 cm may be below 0°C at elevations above 3400 m in the Uintas (Bockheim and Koerner, 1997). Active rock glaciers have been reported from the Uintas (Grogger, 1974). However, these reports were based solely on observations of typical rock glacier morphology; no rock glacier movement was documented. Permafrost has not been found in the upper 100 cm of soil profiles anywhere in the range, but extensive interstitial ice was encountered in talus at 2480 m in late summer in the western Uintas (Bauer and Chapman, 1986).

The bedrock in the area is the Uinta Mountain Group, a thick sequence of sandstones, shales, and poorly metamorphosed quartzites of late Precambrian age (Ritzma, 1959). The alpine region consists predominantly of an upland ridge system identified as a remnant of the Eocene- to Miocene-aged Gilbert Peak Erosional Surface (Bradley, 1936).

Soil parent materials are dominantly till and colluvium in the upper montane and subalpine zones and colluvium and residuum in the alpine zone. The parent materials are often capped with a silt layer ranging from 10 to 48 cm (mean = 21 cm) in thickness (Bockheim and Koerner, 1997). The ages of the glacial materials are not known, but those in the valleys are similar to Pinedale deposits in the Wind River Mountains (sensu Richmond, 1965) and likely to be of late Wisconsin (ca. 14–30 ka BP) age (Grogger, 1974). Drifts along the margins of the alpine plateaus are pre-late Wisconsin because they occur above the lateral moraines graded to the Pinedale termini (Atwood, 1909; Grogger, 1974). There is no evidence for glaciation, such as scoured and striated bedrock or reworking of the Oligocene-age Bishop Conglomerate, on the alpine uplands. The abundance of relict large-scale patterned ground features argues for an intensive periglacial climate during the last glacial maximum (Grogger, 1974).

3. Methods and materials

Detailed descriptions were made of 32 pedons on landforms within plant communities representing the three ecoclimatic zones following criteria established by the Soil Survey Division Staff (1993) (Table 1). Sites were chosen to maximize local landscape stability, and included moraine crests, outwash terraces, and flat alpine uplands. Thirteen pedons were sampled in the upper montane forest, five in subalpine forest, and 14 in the alpine. Samples were collected from each horizon to a depth of 100 cm, except where bedrock or large boulders prevented digging to that depth.

Analytical methods used in this study are reported by code in Soil Survey Staff (1996). A total of 163 samples were analyzed for pH (method 8C1a), easily oxidizable organic C (6A1a), total N (6B2a), extractable P (6S3), cation-exchange capacity (5A8), exchangeable acidity (6Ha, 6H5), extractable Al (6G1) and particle-size distribution with silt and sand fractionation (3A, 3A1). Base cations were extracted with NH_4OAc using the method of Hammer and Lewis (1987). Bulk density was estimated from organic C measurements using Eq. 2 of Alexander (1989).

Profile quantities of nutrients and weathering products were calculated by taking the product of horizon thickness, bulk density, and the specific soil property, which were

Table 1
Site factors for and classification of pedons sampled in the southwestern Uinta Mountains, Utah

Life zone	Elevation (m)	Pedons	Parent materials[a]	No. of pedons				
				Eutrocryepts	Dystrocryepts	Haplocryalfs	Haplocryolls	Cryorthents
Upper montane	2700–3000	SFAC-97-1-3, SFAC-97-5-9, 11-15	loess / till (8), till (1), loess / lacustrine (1), loess / outwash (3)	4	4	2	1	2
Subalpine forest	3000–3400	U92-5, SFAC-97-10, 16-18,	loess / till (5)	0	3	0	0	2
Alpine tundra	3400–3850	U90-1-3, 5, 6, U92-1, U92-1, 6-8, U97-1-3, 5-6	loess / residuum (3), loess / colluvium (2), loess / till (3), residuum (3), colluvium (1), till (1), loess / alluvium (1)	6	2	4	1	1

[a] No. of pedons in parentheses.

then summed to a depth of 100 cm. Corrections were made for coarse fragments, which commonly accounted for 50 to 75% of the profile volume or mass of materials not enriched in silt. Soil properties among ecoclimatic zones were compared using one-way analysis of variance.

4. Results

Soils representative of five great groups in *Soil Taxonomy* (Soil Survey Staff, 1998) were identified in the three ecoclimatic zones. Eutrocryepts and Dystrocryepts were the dominant great groups, accounting for 59% of the 32 pedons examined, followed by Haplocryalfs (19%), Cryorthents (16%), and Haplocryolls (6%) (Table 1). Similar proportions of soil great groups were reported in alpine and subalpine regions of the Medicine Bow Mountains of Wyoming (Rahman et al., 1997).

4.1. Upper montane forest

The upper montane forest extends from 2700 to 3000 m along the south slope of the Uintas. This ecoclimatic zone features dominantly till (Table 1) of a gravelly coarse sand or gravelly fine sandy loam texture. The coarse fragment (≥ 2 mm) content of these materials commonly ranges from 20 to 65%. Soils in the upper montane forest were all located on till mapped as Pinedale or younger in age (ca., 15–25 ka year BP) (Grogger, 1974). In addition, the soils are similar to post-Pinedale soils described in the upper montane forest of the Medicine Bow Mountains of Wyoming (McCahon and Munn, 1991) but lack the development of the older post-Bull Lake soils.

Soils of the upper montane forest are dominantly Eutrocryepts and Dystrocryepts with a thin forest floor over a thin A horizon developed in silt, a moderately thick (mean = 18 cm) E horizon and a cambric (Bw) horizon from till (see pedon SFAC-97-14, Table 3). The sola average 55 cm in thickness (Table 2). The soils support lodgepole pine with a grouse whortleberry (*Vaccinium scoparium*) understory. The lodgepole pine generally ranges from 100 to 125 years in age, or less in areas affected by fire (S. Goodrich, Ashley National Forest, personal communication).

Typic Haplocryalfs occur in the upper montane forest (see pedon SFAC-97-3 in Table 3). Although these soils often have a silt cap, the argillic (Bt) horizon is formed in the underlying fine sandy loam glacial till (Tables 3, 4). Haplocryolls were identified during the course of the study, one of which (SFAC-97-6, Table 3) is derived from 10 cm of silt-rich material over lacustrine sediment in a proglacial basin.

4.2. Subalpine forest

The subalpine forest occurs from 3000 to 3400 m along the southern slope of the Uinta Mountains. All of the soils examined in this ecoclimatic zone were derived from silt-rich materials, averaging 16 cm in thickness, over till. The till contains 50 to 65%

Table 2
Soil properties by ecoclimatic zone in the southwestern Uinta Mountains

Property	Units	Upper montane forest	Subalpine forest	Alpine tundra	Mean square[a] Between groups	Mean square[a] Within groups	F[b]	P[c]
Loess thickness	cm	13	16	16	26.5	158	0.168	0.85
Profile silt	Mg ha^{-1}	2262	2307	1823	807039	866375	0.931	0.40
A horizon thickness	cm	9	9	14	112	59.0	1.90	0.17
E horizon thickness	cm	18	9	3	1607	4067	5.73	0.008
CDE, B horizon[d]		17	12	19	79.6	72.4	1.10	0.35
Clay, A or E horizon	%	9	6	12	89.2	90.6	0.98	0.38
Clay, B horizon	%	7	4	12	120	69.0	1.74	0.19
Clay ratio (B/A or E)		1.5	0.6	1.1	1.66	1.74	0.952	0.40
Solum thickness	cm	55	46	73	1834	821	2.23	0.12
Profile clay	Mg ha^{-1}	674	422	936	547584	39056	1.38	0.27
Profile exch. Ca	kmol(+) ha^{-1}	277	121	312	68373	49816	1.37	0.27
Profile exch. Mg	kmol(+) ha^{-1}	63	30	81	4835	3561	1.36	0.27
Profile exch. bases	kmol(+) ha^{-1}	352	158	408	115422	80613	1.43	0.26
Profile exch. acidity	kmol(+) ha^{-1}	404	461	596	128799	142554	0.903	0.42
Profile extr. Al	kmol(+) ha^{-1}	76	242	270	88158	28651	3.08	0.070
Profile exch. cations	kmol(+) ha^{-1}	756	618	1004	356710	347060	1.03	0.37
Profile extr. P	mol ha^{-1}	1089	884	1959	3457	2226	1.55	0.23
Profile total N	mol ha^{-1}	49	53	112	15.4	3.3	4.68	0.017
Profile organic C	kg m^{-2}	4.6	2.4	7.7	61.8	18.1	3.42	0.046

[a] Based on single-factor analysis of variance.
[b] F statistic.
[c] Probability of significantly larger F statistic.
[d] Color development equivalence (after Buntley and Westin, 1965).

coarse fragments and is likely of Pinedale age. The soils in this zone are dominantly Dystrocryepts and Cryorthents with a common horizon sequence containing a thin forest floor, a thin A or E horizon developed in silt, and a thin 2Bw horizon developed in the underlying till (pedons U92-5 and SFAC97-16, Table 3). The sola average 46 cm in thickness (Table 2).

The soils support Engelmann spruce and subalpine fir that are generally quite old (350–500 years), largely because of the infrequency of fires (S. Goodrich, Ashley National Forest, personal communication).

4.3. Alpine tundra

Alpine tundra occurs from 3400 m to the highest summit in the Uintas, which is Kings Peak at 4099 m. Although glacial deposits occur on the floors of the highest cirques in this zone, most of the soil parent materials are residuum and colluvium derived from sediments of the Uinta Mountain Group. The ages of these non-glacial parent materials are unknown. However, soil development is comparable to post-Bull Lake soils of the Medicine Bow Mountains in Wyoming (McCahon and Munn, 1991).

Table 3
Morphological properties[a] of representative pedons in the eastern Uinta Mountains, Utah

Horizon	Lower depth (cm)	Munsell color (moist)	Texture	Structure		Consistence		Roots	Lower boundary	Cutans/ siltans
				Primary	Secondary	Moist	Wet			
SFAC-97-14 Typic Dystrocryept, Upper Montane Forest										
A	12	10YR 4/3	sil	2msbk	2vfgr	vfr	ss/ps	1co,m	cw	
2E	25	10YR 6/3	sl	2cosbk	2msbk	vfr	ss/ps	1m,f,vf	cw	
2Bw	59	5YR 5/4	ls	1msbk	2vfgr	vfr	ss/po		cw	
2C	90	7.5YR 6/4	sl	1msbk	sg	fr	ss/ps			siltans
SFAC97-7 Typic Eutrocryept, Upper Montane Forest										
A	6	10YR 4/4	sil	2vfgr		vfr	ss/ps	1f, 2vf	aw	
2E1	12	10YR 7/2	sl	2fgr	2vfgr	vfr	ss/ps	1f, 2vf	aw	
2E2	36	10YR 6/3	ls	1fsbk		fr	so/ps	2f,vf	cw	
2BC	58	7.5YR 6/3	s	sg		lo	so/po	1f	gw	
2C	100	7.5YR 5/4	s	sg		lo	so/po	1f		siltans
SFAC-97-3 Typic Haplocryalf, Upper Montane Forest										
A2	13	10YR 5/3	sil	2msbk	2fgr	fr	ss/ps	1co, 2f,vf	aw	
2E	41	10YR 6/4	sl	2fsbk	2vfsbk	fr	ss/ps	1m,f	cw	
2Bw	70	7.5YR 5/6	sl	2msbk	2fsbk	fr	ss/ps	1m	cw	siltans
2Bt	102	7.5YR 4/4	sl	2msbk	2fsbk	fr	ss/ps	1m		1mkpf cutans
SFAC-97-6 Typic Haplocryoll, Upper Montane Forest										
A	10	7.5YR 2.5/1	l	1fgr		fr	ss/p	1m,f, 2vf	aw	
2AB	47	7.5YR 2.5/2	scl	2msbk	2fsbk	vfr	ss/ps	1m,f,vf	aw	
2Bw	66	7.5YR 3/3	fsl	1cosbk	1vfsbk	fr	s/ps	1m,f,vf		
U92-5 Typic Dystrocryept, Subalpine Forest										
Oi	1									
Oe/Oa	6									
E/B	28	5YR 5/3, 3/3	sil	1msbk		fr	ss/ps	1m	aw	
2E	43	5YR 4/3	sl	1msbk		fr	ss/ps	1co,m	cw	
2Bw	86	2.5YR 3/4	ls	sg		vfr	so/po	0		
SFAC-97-16, Typic Dystrocryept, Subalpine Forest										
Oi	1									
Oe	5									
Oa	8									
A	18	7.5YR 5/4	l	1msbk	2mgr	fr	s/ps	1co,m,f	cw	
2Bw	24	7.5YR 5/6	stcosl	3mgr	3fgr	fr	ss/ps	1m,f	gw	
2C	50	7.5YR 4/4	stmsl	2msbk	3fgr	vfr	ss/po	1m,vf		
U97-3 Typic Eutrocryept, Alpine Tundra										
Oa	1									
A	10	10YR 2/1	msl	2vfgr		vfr	ss/ps	3m, 2vf, 1f	aw	
Bw	33	7.5YR 5/3	fsl	2fpl	1fgr	vfr	ss/ps	2vf, 1f	cw	
2Bw1	53	7.5YR 5/3	gmsl	2fpl	2vfsbk	fr	ss/ps	2vf	gw	v1npo cutans
2Bw2	76	7.5YR 4/4	l	2vfsbk		fr	ss/ps	1vf		v1npo cutans

Table 3 (*continued*)

Horizon	Lower depth (cm)	Munsell color (moist)	Texture	Structure		Consistence		Roots	Lower boundary	Cutans/siltans
				Primary	Secondary	Moist	Wet			
U97-5 Typic Haplocryalf, Alpine Tundra										
Oa	1									
A	6	10YR 2/2	l	2fgr		fr	ss/ps	2vf,f	aw	
Bw	12	7.5YR 3/2	l	2fgr		fr	ss/ps	2vf,f	ab	
2Bw	24	7.5YR 4/3	kls	2fsbk	2fgr	fr	ss/ps	1f	cw	
2BE	46	7.5YR 5/4	kls	1fsbk	1fgr	fr	ss/po	1vf	aw	
2Bt1	74	5YR 4/6	kfsl	2msbk	2fsbk	fi	ss/ps	1f	cw	3npfpo cutans
2Bt2	100	5YR 4/4	kmsl	2msbk	2fsbk	fi	ss/ps	1f		3npfpo cutans

[a]Abbreviations given in Soil Survey Division Staff (1993).

Coarse fragments comprise 20 to 60% of the volume or mass of materials not enriched in silt in the alpine tundra. Most of the soils in the alpine zone have a silt cap; Eutrocryepts are most common (Table 1). A common horizon sequence in alpine soils is a thin A horizon developed in silt over a moderately thick 2Bw (60 + cm) developed in colluvium (pedon U97-3, Table 3). Haplocryalfs are surprisingly common in the alpine zone and contain many thin cutans on ped faces and clay-enriched Bt horizons (pedon U97-5, Table 3).

5. Discussion

5.1. Distribution of silt

Twenty-five of the 32 pedons contained a silt-enriched cap that ranged from 4 to 50 cm and averaged 15 cm in thickness. There were no significant differences in thickness of the silty mantle among the three ecoclimatic zones, averaging 13, 16, and 16 cm for the upper montane forest, the subalpine forest, and the alpine tundra, respectively (Table 2). The profile content of silt likewise was unrelated to ecoclimatic zone, averaging 2260, 2310, and 1820 Mg ha^{-1} for the upper montane forest, subalpine forest, and alpine tundra, respectively. These data suggest that silt has been contributed more or less equally at all elevations studied (ca. 2700–3850 m). Local factors, including relief, topographic position, and possibly niveo-eolian processes may be responsible for thickness variations among sites.

As the soil parent materials are dominantly quartzite, the silt must be of eolian origin. The silt cap fits common definitions of ''alpine loess'' described elsewhere in the Rocky Mountains (Thorn and Darmody, 1980; Birkeland et al., 1987; Litaor, 1987; Munn and Spackman, 1990; Dahms, 1993; Dahms and Rawlins, 1996) in that it lies disconformably on coarser-textured materials, is ubiquitous rather than localized, has silt concentrations ranging from 32 to 59% (mean = 45% silt), and is often calcareous (Tables 4, 5).

The origin of the silt is uncertain, but is likely derived from the Uinta Basin to the south (Bockheim and Koerner, 1997). Likewise, the age of the silt is an enigma.

Table 4
Particle-size distribution of representative pedons in the eastern Uinta Mountains, Utah

Horizon	Lower depth (cm)	Clay (< 2 μm)	F silt (2–5 μm)	Co silt (5–50 μm)	Total silt	VF sand (0.1–0.05 mm)	F sand (0.25–0.10 mm)	M sand (0–5–0.25 mm)	Co sand (1–0.5 mm)	VCo sand (2–1 mm)	Total sand	> 2 mm
		% by mass										
SFAC-97-14 Typic Dystrocryept, Upper Montane Forest												
A	12	4.1	20.8	23.2	44	10.8	16.7	9.5	8.5	6.4	51.9	20
2E	25	2.8	9.7	12.8	22.4	9.4	25.6	13.5	15.1	11.2	74.7	40
2Bw	59	3.7	8.4	12.6	21.1	9.8	28.4	16.8	12.6	7.7	75.3	30
2C	90	3.1	12.0	13.8	25.9	9.5	25.7	12.5	13.4	9.9	71.0	30
SFAC97-7 Typic Cryorthent, Upper Montane Forest												
A	6	5.2	14.1	32.7	46.8	13.0	14.1	8.0	7.9	5.0	48.0	30
2E1	12	2.9	19.0	21.6	40.6	8.6	16.1	10.5	13.0	8.2	56.5	30
2E2	36	2.8	10.3	11.7	22.0	6.4	19.7	15.3	20.7	13.2	75.3	70
2BC	58	1.6	2.9	4.4	7.3	4.3	29.2	22.4	23.3	11.9	91.1	70
2C	100	1.4	1.7	4.0	5.6	8.1	29.1	24.3	19.5	11.9	93.0	75
SFAC97-3 Typic Haplocryalf, Upper Montane Forest												
A2	13	5.3	22.1	23.0	45.1	11.0	16.2	9.6	8.1	4.7	49.6	30
2E	41	5.3	17.7	17.3	35.0	8.7	21.5	13.1	11.2	5.3	59.7	50
2Bw	70	7.1	17.5	15.9	33.4	7.7	22.0	12.3	10.3	7.0	59.5	30
2Bt	102	13.2	13.7	16.3	30.0	7.5	22.0	11.5	9.3	6.4	56.9	25
SFAC-97-6 Typic Haplocryoll, Upper Montane Forest												
A	10	20.8	16.5	18.7	35.2	9.1	19.8	7.8	5.0	2.4	44.0	0
2AB	47	20.8	11.1	13.2	24.3	9.3	29.6	11.0	3.8	1.3	55.0	0
2Bw	66	19.0	11.5	12.2	23.6	8.1	31.0	12.5	4.5	1.3	57.4	0

U92-5 Typic Cryorthent, Subalpine Forest												
E/B	28	12.1	27.9	25.6	53.5	12.9	12.3	5.1	2.8	1.3	34.3	50
2E	43	2.3	6.6	10.3	16.9	12.2	36.3	17.7	9.1	5.5	80.8	65
2Bw	86	1.5	3.2	7.5	10.6	13.2	44.3	17.6	7.4	5.5	88.0	65
SFAC-97-16 Typic Dystrocryept, Subalpine Forest												
A	18	7.9	22.8	26.4	49.3	14.5	14.1	6.4	4.9	3.0	42.9	20
2Bw	24	6.1	14.4	15.8	30.1	9.0	13.5	8.8	11.4	21.1	63.8	40
2C	50	6.4	21.5	18.0	39.5	9.5	14.5	7.5	9.6	13.0	54.1	70
U97-3 Typic Eutrocryept, Alpine Tundra												
A	10	9.8	10.1	12.2	22.3	6.0	24.6	17.9	11.6	7.8	67.9	0
Bw	33	10.3	18.3	17.7	36.0	8.0	18.3	15.2	8.3	4.0	53.8	10
2Bw1	53	12.0	14.7	15.6	30.3	7.7	18.7	18.5	9.8	3.0	57.7	25
2Bw2	76	14.6	14.2	22.1	36.3	5.9	14.9	16.6	8.5	3.2	49.1	20
U97-5 Typic Haplocryalf, Alpine Tundra												
A	6	25.2	24.2	24.5	48.7	9.3	10.7	3.2	1.7	1.3	26.2	5
Bw	12	20.2	23.3	22.1	45.5	9.4	14.7	5.8	2.8	1.6	34.3	5
2Bw	24	6.0	6.8	7.7	14.5	7.3	36.9	17.5	11.1	6.7	79.5	40
2BE	46	4.1	5.1	6.6	11.7	6.2	39.1	24.0	10.4	4.5	84.2	40
2Bt1	74	15.4	10.1	11.6	21.7	7.8	30.4	14.6	6.8	3.3	62.9	40
2Bt2	100	18.6	6.5	8.2	14.6	5.8	28.1	17.7	9.5	5.8	66.7	40

Table 5
Chemical properties of representative pedons in the eastern Uinta Mountains, Utah

Horizon	Ex Ca	Ex Mg	Ex Na	Ex K	Sum bases	Ex acidity	Extr Al	CEC-Sum cations	CEC NH4OAc	Al sat	PBS Sum	PBS NH4OAc	Org C	TKN	pH $CaCl_2$	pH H_2O	Extr P (mg/kg)
	cmol(+)/kg									%							
SFAC-97-14 Typic Dystrocryept, Upper Montane Forest																	
A	2.3	0.4	TR[a]	0.1	2.8	2.7	0.5	5.5	4.9	15	51	57	0.4	0.1	5	5.6	9.6
2E	1.4	0.4	TR	TR	1.9	2.2	0.6	4.1	3.4	24	46	56	0.2	0	4.7	5.4	8.8
2Bw	1	0.4	TR	0.1	1.5	1.5	0.5	3	2.8	25	50	54	0.1	0	4.7	5.4	1.2
2C	1.2	0.4	TR	0.1	1.7	2.1	0.6	3.8	3.3	26	45	52	0.2	0	4.7	5.3	1.7
SFAC97-7 Typic Cryorthent, Upper Montane Forest																	
A	5.0	0.8	0	0.5	6.3	6.9	0.3	13.2	10.4	5	48	61	1.7	0.1	4.9	5.4	95
2E1	2.2	0.4	0	0.2	2.8	3.6	0.8	6.4	5.0	22	44	56	0.5	0	4.5	5.1	24
2E2	2.1	1.2	TR	0.2	3.5	3.2	0.5	6.7	4.5	13	52	78	0.4	0	4.6	5.2	24
2BC	1.2	0.8	TR	0.1	2.1	1.8	0.2	3.9	2.7	9	54	78	0.1	0	4.8	5.4	16
2C	1.0	0.4	TR	TR	1.5	0.9	0.2	2.4	2.1	12	63	71	0.1	0	4.8	5.4	14
SFAC97-3 Typic Haplocryalf, Upper Montane Forest																	
A2	1.9	0.4	0	0.1	2.4	7.0	2.1	9.3	7.5	47	26	32	1.0	0.1	4.2	4.8	3.6
2E	2.6	0.4	0	0.1	3.1	5.0	1.3	8.1	6.5	30	38	48	0.3	0	4.5	5.1	2.5
2Bw	1.9	0.4	0	TR	2.3	3.8	1.2	6.1	5.1	34	38	45	0.2	0	4.6	5.3	0.6
2Bt	2.6	1.2	TR	0.1	3.9	3.7	1.3	7.6	6.8	25	51	57	0.1	0	4.4	5.1	0.2
SFAC-97-6 Typic Haplocryoll, Upper Montane Forest																	
A	17.3	2.3	0.1	0.2	19.9	20.9	0.1	40.8	34.6	1	49	58	7.1	0.4	5.1	5.7	0.4
2AB	8.2	1.6	TR	0.2	10.0	14.7	1.1	24.7	18.5	10	40	54	1.7	0.1	4.8	5.5	0.2
2Bw	7.1	1.6	TR	0.1	8.8	14.0	1.1	22.8	17.6	11	39	50	1.7	0.1	4.8	5.5	0.4

U92-5 Typic Cryorthent, Subalpine Forest																	
E/B	6.4	1.2	0.05	0.1	7.8	10.7		18.4	15.5		42	50	1.2	0.06		4.6	18
2E	1.2	0.4	0.05	0.1	1.8	3.9		5.6	4.5		31	39	0.3	0.01		4.6	30
2Bw	0.7	0.0	0.05	0.05	0.8	2.2		3.0	2.3		27	35	0.1	0.01		4.7	12
SFAC-97-16 Typic Dystrocryept, Subalpine Forest																	
A	4.4	0.8	TR	0.1	5.3	8.1	2.3	13.4	11.4	30	40	46	0.9	0.1	4.5	5.2	1.4
2Bw	4.5	0.8	TR	0.1	5.4	7.4	2.6	12.8	11.6	33	42	47	0.5	0.1	4.6	5.2	0.4
2C	2.2	0.8	TR	0.1	3.1	8.7	4.2	11.8	10.1	58	26	31	0.3	0.1	4.3	5.0	0.4
U97-3 Typic Eutrocryept, Alpine Tundra																	
A	34.2	5.4	TR	0.8	40.4	11.3	0.1	51.7	46.4	0	78	87	10.0	0.8	6.1	6.3	8.1
Bw	7.6	2.0	TR	0.2	9.8	5.8	0.1	15.6	12.1	1	63	81	0.9	0.1	5.1	5.8	3.0
2Bw1	5.1	1.6	TR	0.1	6.8	6.7	1.3	13.5	11.0	16	50	62	0.5	0.1	4.6	5.3	2.8
2Bw2	3.4	0.8	TR	0.1	4.3	11.2	6.1	15.5	10.7	59	28	40	0.4	0.1	4.1	4.7	6.1
U97-5 Typic Haplocryalf, Alpine Tundra																	
A	28.3	3.8	0.1	0.5	32.7	19.2	0.1	51.9	45.0	0	63	73	9.6	0.7	5.5	5.9	1.8
Bw	11.5	2.0	0.1	0.2	13.8	14.2	0.1	28.0	27.1	1	49	51	3.6	0.3	5.6	6.2	0.9
2Bw	4.8	1.2	TR	0.1	6.1	2.5	0.1	8.6	6.8	2	71	90	0.4	0.1	5.6	6.3	2.1
2BE	2.2	0.4	0	TR	2.6	2.3	0.1	4.9	3.2	4	53	81	0.2	0.1	5.2	6.0	1.7
2Bt1	4.0	0.8	TR	0.1	4.9	5.7	1.9	10.6	10.3	28	46	48	0.3	0.1	4.6	5.3	2.3
2Bt2	6.1	1.6	TR	0.2	7.9	7.1	3.0	15.0	12.4	28	53	64	0.2	0	4.5	5.2	3.2

[a] Trace quantities.

Because the silt covers landforms from mid-Holocene to pre-late Wisconsin in age, it is tempting to suggest that it originated during a mid-Holocene warm period recorded in the central Rocky Mountains (Elias, 1985). However, a single eolian silt deposition event should have resulted in abundant buried soils, but these are uncommon at the sample sites except in depositional basins. A second option is that silt was deposited during each glacial event but was eroded or cryoturbated during interglacials, yielding a relatively uniform cover throughout the south slope of the eastern Uintas. Clearly, further study is needed to date the eolian silt in the Uinta Mountains.

5.2. Soil-forming processes

Argilluviation (clay translocation) is a predominant soil-forming process in the Uinta Mountains and is most pronounced in soils of the upper montane forest. This is reflected by the ratio of clay in the upper B horizon to that in the A or E horizon. This ratio is 0.6 in subalpine soils, 1.1 in alpine soils, and is 1.5 in soils of the upper montane forest (Table 2). Soils of the upper montane often contain thin cutans on ped surfaces. Burns (1980) and McCahon and Munn (1991) have also reported clay translocation in soils of the subalpine and upper montane regions of the central Rocky Mountains.

Although it is less common than in upper montane soils, argilluviation also occurs in the alpine soils of the Uintas. Four pedons in the alpine zone contain argillic horizons that range from 30 + to 72 + cm in thickness. The argillic horizons suggest that the alpine soils are older than soils on glacial landforms at lower elevations. In the Medicine Bow Mountains, argillic horizons average 40 to 50 cm in thickness in post-Pinedale soils (ca. 14–30 ka BP) and 53 to 80 cm in post-Bull Lake soils (ca. 130 ka BP) (McCahon and Munn, 1991). In addition, soil development may proceed more rapidly in the alpine zone than at lower elevations. Field and laboratory data suggested a more rapid rate of development for soils in the alpine zone of the Colorado Front Range than for those at lower elevations, in spite of the cold climate (Birkeland et al., 1987).

Silt translocation is prevalent in soils of all ecoclimatic zones and great soil groups in the Uinta Mountains. Seventeen of the 32 pedons described in the Uinta Mountains had siltans, primarily in the 2BC and 2C horizons. Alpine soils of the northern and central Rocky Mountains commonly feature silt accumulation in the subsoil and caps on coarse fragments (Burns, 1980; Munn and Spackman, 1990).

Base cycling is more prevalent in alpine soils than in those of the other ecoclimatic zones (Tables 2 and 5). The amounts of exchangeable Ca and the sum of base cations (Ca + Mg + K + Na) are greater in the alpine soils than in those of the other zones (Table 2). In addition, the concentration of Ca in above-ground tissues of *Geum* is greater than in other non-woody species in the alpine zone of the Uinta Mountains (Fig. 2). These data suggest the *Geum rossii*-sedge communities, which dominate the alpine zone of the Uinta Mountains appear to be especially capable of cycling base cations.

Weathering seems to be greater in the alpine soils than in the subalpine and upper montane soils. Solum thickness and profile quantities of clay, exchangeable acidity and extractable Al are all greater in the alpine soils than in the subalpine and upper montane soils (Table 2). Other studies have emphasized the magnitude of chemical weathering in

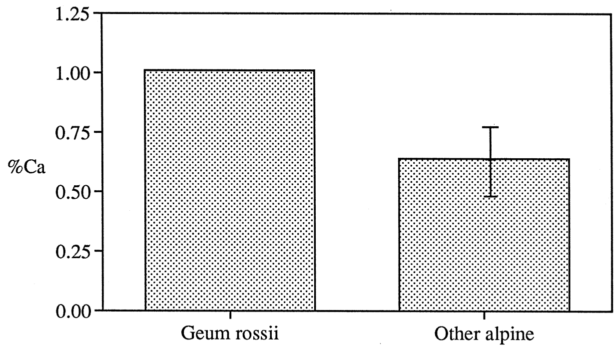

Fig. 2. Calcium concentrations in above-ground tissues of *A.* (*Geum*) *rossii* and an average of eight other nonwoody alpine plants, including *Artemisia scopularum, C. rupestris, C. aquatilis, C. scirpoidea, Polemonium viscossium, Trifolium nanum, D. caespitosa* and *K. myosuroides.*

alpine regions (Reynolds and Johnson, 1972; Brown and Lund, 1991). However, the alpine soils in the Uinta Mountains may be older than those at lower elevations, and this could explain the above differences.

The C content of the alpine soils is significantly ($p = 0.046$) greater than that of the subalpine and upper montane soils (Table 2). This may result partially from the greater age of these soils but also from the fact that alpine soils tend to have high profile C contents because of abundant below-ground production and environmental conditions that limit turnover of organic matter (Atkin et al., 1996; Bockheim et al., in press).

The alpine soils also contain significantly ($p = 0.017$) greater amounts of total N than soils of lower elevations (Table 2), because of their increased organic matter contents. They also contain nearly twice as much extractable P as soils at lower elevations, though the differences were not significant (Table 2). The greater amount of P in alpine soils may also be related to the increased organic matter, as most of the P in alpine soils is organically bound (Bowman et al., 1993).

6. Conclusions

As there were no significant differences in silt-cap thickness and soil-profile quantities of silt, the silt is somewhat uniformly deposited throughout the upper montane forest, subalpine forest, and alpine tundra in the Uinta Mountains, with some local variations related to topography. The greater profile quantities of clay, exchangeable acidity, and extractable Al in the alpine soils may reflect their greater age and increased rate of weathering. The abundance of Eutrochrepts and Haplocryalfs in the alpine zone and high profile quantities of Ca suggest that the alpine soils cycle large amounts of Ca. The above-ground concentrations of Ca are particularly high in *A.* (*Geum*) *rossii* communities. Profile quantities of C, N, and P are largest in the alpine soils, possibly because of greater below-ground production and slower turnover of organic matter.

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