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Soil Development and Glacial History, West Fork of Beaver Creek, Uinta Mountains, Utah

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Abstract

The dominant mechanisms of soil formation on a sequence of Smiths Fork, Blacks Fork, and Pre–Blacks Fork moraines in West Fork of Beaver Creek, Uinta Mountains, Utah, (equivalent to Pinedale, Bull Lake, and Pre–Bull Lake moraines of the Wind River Range, respectively) are clay translocation (argilluviation), increasing soil redness (rubification), and the accumulation of organic matter (melanization) and silt-sized particles. The quantity of clay-sized particles and degree of soil redness increase with soil age, but clay accumulation may plateau in the oldest soils. In contrast, the quantity of accumulated organic matter and abundance of silt-sized particles do not appear to correlate to soil age. The Smiths Fork moraine, interpreted to be MIS-2 in age, has two crests that have distinctly different amounts of clast weathering and soil development. The outer Smiths Fork crest displays weathering that is more comparable to that of the Blacks Fork moraine than to the inner Smiths Fork crest. This weathering contrast is related to an age difference between the two crests, but a precise chronology of the Smiths Fork moraines cannot be determined from these data.

Introduction

Many glacial histories in the western United States rely on the degree of soil development to determine the relative ages of glacial landforms and to correlate glacial deposits from one mountain range to another (e.g., Blackwelder, 1915; Richmond, 1965; Swanson, 1985; Burke and Birkeland, 1979; Berry, 1987; Birkeland and Burke, 1988; Hall and Shroba, 1993, 1995; Dahms, 2004). Such soil chronosequence studies have also been applied to the local and regional correlation of other landforms including lava flows, marine terraces, and alluvial fans (e.g., McFadden et al., 1986; Muhs et al., 1987; Reheis et al., 1992). The concept of the soil chronosequence is derived from Jenny's (1941) model of soil formation—that a soil is the result of five main soil-forming factors: climate, biota, topography, parent material, and time of soil formation. If age is the only soil-forming factor that varies within a group of soils, then differences in the degree of development of the soils are related to different time intervals of soil formation.

One of the best-resolved glacial chronologies in the western United States is that of the Pinedale and Bull Lake glaciations in the Wind River Range, Wyoming. Blackwelder (1915) correlated prominent moraines on both sides of the range to the Wisconsin and Illinoian glaciations of the midwestern United States, but a more precise chronology for the Pinedale and Bull Lake glaciations remained elusive for almost a century. Cosmogenic nuclide surface-exposure dating of moraine boulders confirmed that the Pinedale glaciation occurred during Marine Isotope Stage 2 (MIS-2) (ca. 21 ka; Gosse et al., 1995), and that many Bull Lake moraines were deposited during MIS-6 (ca. 150 ka; Anderson et al., 1996; Phillips et al., 1997). However, the surface-exposure ages of the inner Bull Lake moraines are younger than MIS-6, suggesting they may have been deposited during MIS-5d (ca. 108 ka; Phillips et al., 1997). Soil-chronosequence studies agreed with this interpretation. The soils in the inner Bull Lake moraines are less developed than the outer Bull Lake soils, and this contrast was interpreted as an age difference between the outer and inner moraines (Coleman and Pierce, 1986; Hall and Shroba, 1993, 1995; Chadwick et al., 1997). However, subsequent uranium-series disequilibrium dating of pedogenic carbonate in glaciofluvial terraces related to the inner Bull Lake moraines precluded the possibility of a younger age for the inner Bull Lake moraines. Ages of ca. 150 ka demonstrated that the terraces, and the correlative inner moraines, were deposited during MIS-6 (Sharp et al., 2003). Nevertheless, the possibility remains that glacial deposits are preserved from MIS-4, 5b, or 5d glaciations elsewhere in the western United States.

Investigations of soil development in the Uinta Mountains (Bockheim and Koerner, 1997; Bockheim et al., 2000), and in many other locations in the western United States (e.g., Birkeland et al., 1987; Litaor, 1987; Dahms, 1993, Reheis et al., 1995; Dahms and Rawlings, 1996; Muhs and Benedict, 2006), demonstrate that some of the clay-sized particles in the soil profiles accumulate directly from eolian deposition, or by deposition of silt-sized particles that subsequently weather to clay. This dust is commonly derived from the adjacent arid basins. Dahms (1993) used mineralogy to show that the dust deposited in the Wind River Range was derived from the Green River Basin. Similarly, Muhs and Benedict (2006) used immobile trace element chemistry to demonstrate that the silt-sized particles in moraine soils in the Colorado Front Range soils were derived from arid basins to the west. In the Uinta Mountains, Bockheim and Koerner (1997) found that alpine soils are enriched in silt and bases, especially calcium. They concluded that the silt was not derived from the Uinta Mountain Group because these rocks lack calcium-bearing minerals. Instead, intermontane basins to the north and south of the Uinta Mountains were identified as significant sources of calcium carbonate. In the Wind River Range Dahms and Rawlings (1996) measured the highest rates of modern dust deposition in the summer, and suggested an inverse relationship between basin soil moisture and rates of dust deposition in the mountains. Similarly, Muhs and Benedict (2006) hypothesized

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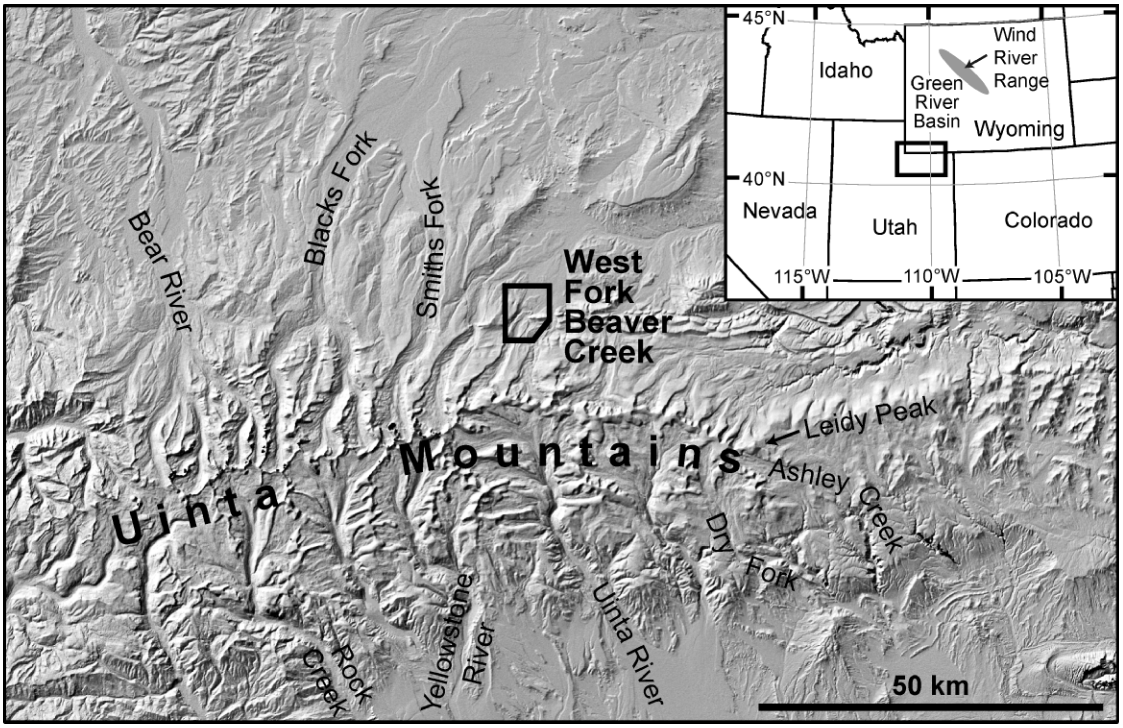

FIGURE 1. Location of the Uinta Mountains in northeastern Utah, U.S.A. The shaded-relief image depicts topography of the range. Black box outlines the study area (Fig. 2).

that most of the silt accumulation occurred during the early to mid-Holocene warm period. This implies that the rate of eolian contributions to alpine soils would be lower during glacial periods than during interglacial periods when effective moisture in the basins was higher (as evidenced by pluvial lakes; e.g., Smith and Street-Perrott, 1983).

In this investigation we use the weathering of surface cobbles and degree of soil development on a sequence of three moraines in the West Fork of Beaver Creek, Uinta Mountains, Utah (Fig. 1), to study both the relative ages of these moraines and the mechanisms of soil formation in these soils. Weathering rind thickness, the soil Profile Development Index (PDI; Harden 1982) parameters of rubification, total texture, clay films, and moist consistence, as well as the quantity of pedogenic clay in the soil profiles, all increase with soil age. An unusual finding is that the proximal portions of the Smiths Fork moraine complex (inferred to be MIS-2 in age) exhibit significantly thinner weathering rinds and weaker soil development than distal portions of this moraine complex. In fact, the weathering of the outer Smiths Fork moraine is more comparable to the Blacks Fork moraine (inferred to be MIS-6 in age) than to the inner Smiths Fork moraine. Without precise moraine ages, this finding is difficult to interpret. We explore two working hypotheses: (1) the outer and inner portions of this moraine complex were deposited during early and late phases of MIS-2, respectively, and a significant amount of weathering and soil development occurred during glacial times; and (2) the outermost portions of this moraine are preserved from an earlier glaciation, perhaps during MIS-4, 5b, or 5d.

Study Area

GEOLOGY OF THE UINTA MOUNTAINS

The Uinta Mountains, in northeastern Utah and northwestern Colorado (Fig. 1), are the topographic expression of an eroded anticline. The mountains are cored by the Precambrian Uinta Mountain Group, a 4- to 7-km-thick sequence of variously metamorphosed iron-stained quartz arenite, subarkosic arenite, and arkosic arenite sandstones, with some shale and minor conglomerate (Hansen, 1965). The mountains are flanked by Paleozoic rocks, predominantly the Mississippian Madison Limestone group and the Pennsylvanian Weber Sandstone (Hansen, 1965).

In his investigation of the glacial history of the Uinta Mountains, Atwood (1909) identified an ''older'' and a ''younger'' glaciation, but also referred to an even older glaciation, which was not formally defined. Bradley (1936) subsequently formalized the local stratigraphic nomenclature for three Uinta glaciations: the Little Dry glaciation (oldest), the Blacks Fork glaciation (''older'' of Atwood, 1909), and the Smiths Fork glaciation (''younger'' of Atwood, 1909). These glaciations were correlated to the Buffalo, Bull Lake, and Pinedale glaciations identified in the Wind River Range (Blackwelder, 1915). Bryant (1992) compiled a 1:125,000-scale surficial and bedrock geological map depicting Pre–Bull Lake, Bull Lake, and Pinedale moraines throughout the Uinta range. Most recently, in a detailed geomorphic map of the entire north flank of the Uinta Mountains, Munroe (2005) returned to the original local terminology of Pre–Blacks Fork, Blacks Fork, and Smiths Fork glaciations. We follow that terminology here.

Two published studies relating soil development and the glacial history of the north flank of the Uinta Mountains document different mechanisms of soil development. Shroba (1988) found no significant differences in the degree of development between Pinedale (Smiths Fork) and Bull Lake (Blacks Fork) soils age near Leidy Peak (30 km east of this field area; Fig. 1), despite the significant age differences between the two moraines. This situation was attributed to the inert nature of the quartz-dominated parent material. In contrast, Zimmer (1996) noted significant differences in soil development between Smiths Fork and Blacks Fork moraine soils in the Smiths Fork drainage

(20 km to the northwest of this field area; Fig. 1). Quantification of the degree of soil development was not possible because no samples of unweathered parent material were found. The soils examined by Zimmer are located below the lower tree line (~2550 m a.s.l.), and have well-developed carbonate morphologies, whereas the soils examined by Shroba (1988) are located at higher elevations where greater soil moisture prevents carbonate accumulation.

THE MORAINES OF WEST FORK OF BEAVER CREEK

The moraine sequence in the West Fork of Beaver Creek is ideally suited to the examination of soil-age relationships in the Uinta Mountains because the soil forming factors are more or less constant across the three separate moraines. First, there is very little climatic variation between the moraines because they are within 3.5 km of each other and differ in elevation by only 125 m. Modern mean annual precipitation is 54 cm and modern mean annual temperature is 1.8°C (Snowpack Telemetry (SNOTEL) site Hole-in-the-Rock; 6 km to the east at an elevation 25–125 m higher than the examined soils; period of record is 1 October 1987 to 30 September 2005). Second, the vegetation is similar on each of the moraines. All soils are located under a tree cover of lodgepole pine (*Pinus contorta*) and quaking aspen (*Populus tremuloides*). Groundcover is dominated by grouse whortleberry (*Vaccinium scoparium*). The outermost moraine at the lowest elevation has up to 10% each of limber pine (*Pinus flexilis*) and sage (*Artemisia tridentada*). Third, soils were sampled on moraine crests, eliminating variation in soil development due to relief or topographic position. The older moraines have more muted topography, indicating that some landform erosion has occurred, but the preservation of closed depressions on the oldest moraines indicates a generally stable landscape with only minimal soil erosion. Finally, the composition of the till is constant because each glaciation eroded the same rock types. For 17 km upstream of the study site, the valley is underlain by the Uinta Mountain Group. The downstream 2 km is underlain by the Mississippian Madison Group (limestone and dolomite). We found only one carbonate clast on or in the moraines; therefore, almost all of the sediment comprising the moraines is derived from the Uinta Mountain Group in the upper part of the valley.

Methods

MAPPING

Quaternary landforms located in the West Fork of Beaver Creek drainage were mapped at a scale of 1:24,000 using air photos (National Aerial Photography Program Black & White and Color Infrared), topographic maps (U.S. Geological Survey 7.5 minute Hole in the Rock (Utah-Wyoming) quadrangle), and field observations of landform morphology. Outwash surfaces were traced to moraines, and cross-cutting relationships between landforms were used to establish the relative ages of moraines and outwash surfaces (Douglass, 2000).

CLAST WEATHERING

Following Colman and Pierce (1981), the thickness of weathering rinds was measured on freshly broken surfaces of 50 arkosic cobbles (64–256 mm) from each of the moraine crests. Only arkosic lithologies were sampled because the non-arkosic lithologies within the Uinta Mountain Group do not contain weatherable minerals and did not show rind development. Clasts were collected from the surface of moraines in transects along the moraine crests.

SOIL DESCRIPTION AND ANALYSIS

Three soils were described and sampled in pits dug on each moraine crest according to the methods of Schoeneberger et al. (2002) and Birkeland (1999). Soil pits were located on moraine crests under representative lodgepole pine–aspen–whortleberry vegetation assemblages, except at lower elevations (Pre–Blacks Fork moraines) where limber pine and sage occur. Every effort was made to expose the full thickness of the soil profiles (all excavations reached at least 92 cm; 5 of 12 pits reached 150 cm); however, no excavation exposed unweathered till. Samples of unweathered parent material were collected from exposures along road cuts and stream banks (Locations A, B, and C on Fig. 2).

Particle-size distribution was measured with sieves and hydrometers (Singer and Janitzky, 1986; Gee and Bauder, 1986). Soil pH was measured on a 1:1 soil-to-deionized water mixture (Singer and Janitzky, 1986), and soil organic carbon content was measured with the Walkley-Black method (Singer and Janitzky, 1986). Bulk density of each horizon was estimated from its organic matter content using the regression developed by Alexander (1989):

$$\text{Bulk density} = 1.827 \times e^{-0.12*\sqrt{OM}}, \quad (1)$$

where OM is the percentage of organic matter in the soil horizon. We assume that organic matter is 58% carbon.

We used three separate methods to quantify soil development. First, a Profile Development Index (PDI; Harden, 1982; Harden and Taylor, 1983; Birkeland, 1999) was calculated using the following seven properties: rubification, melanization, total texture, clay films, structure, moist consistence, and pH. The PDI values are based on the exposed soil profile and are not extrapolated to an assumed soil depth. The values are also not divided by profile thickness. Based on the thicknesses and morphologies of complete soil profiles exposed in stream cuts and road cuts, we believe that our excavations penetrated into soil horizons transitional to unweathered parent material. Therefore, each soil profile represents the majority, but perhaps not all, of the soil development at each location.

Second, total profile accumulations of organic carbon, silt, and clay-sized particles are also used to quantify soil development (Birkeland, 1999). We estimated parent material composition from samples of supraglacial sediment collected from road and stream cuts. We assumed an initial carbon content of zero. The profile accumulation values were corrected (decreased) to account for the volume of the soil occupied by coarse clasts (>2 mm). As with the profile development indices, the profile mass accumulations were based on the exposed profiles.

The third method we used to quantify soil development is the amount of illuvial clay seen in petrographic thin sections of argillic and/or cambic horizons. Thirteen vertically oriented thin sections were prepared according to the methods of Murphy (1986). Thin sections were made from argillic or cambic horizons in all soil profiles except profiles #9 and #10 (Douglass, 2000). Two additional thin sections were prepared from unweathered parent material. Two hundred points were counted on each slide, noting if the point was a grain, illuvial clay film, or void.

Finally, we calculated rates of weathering rind formation and clay accumulation in these soils for three different time periods: (1) between the deposition of the inner Smiths Fork moraine and the

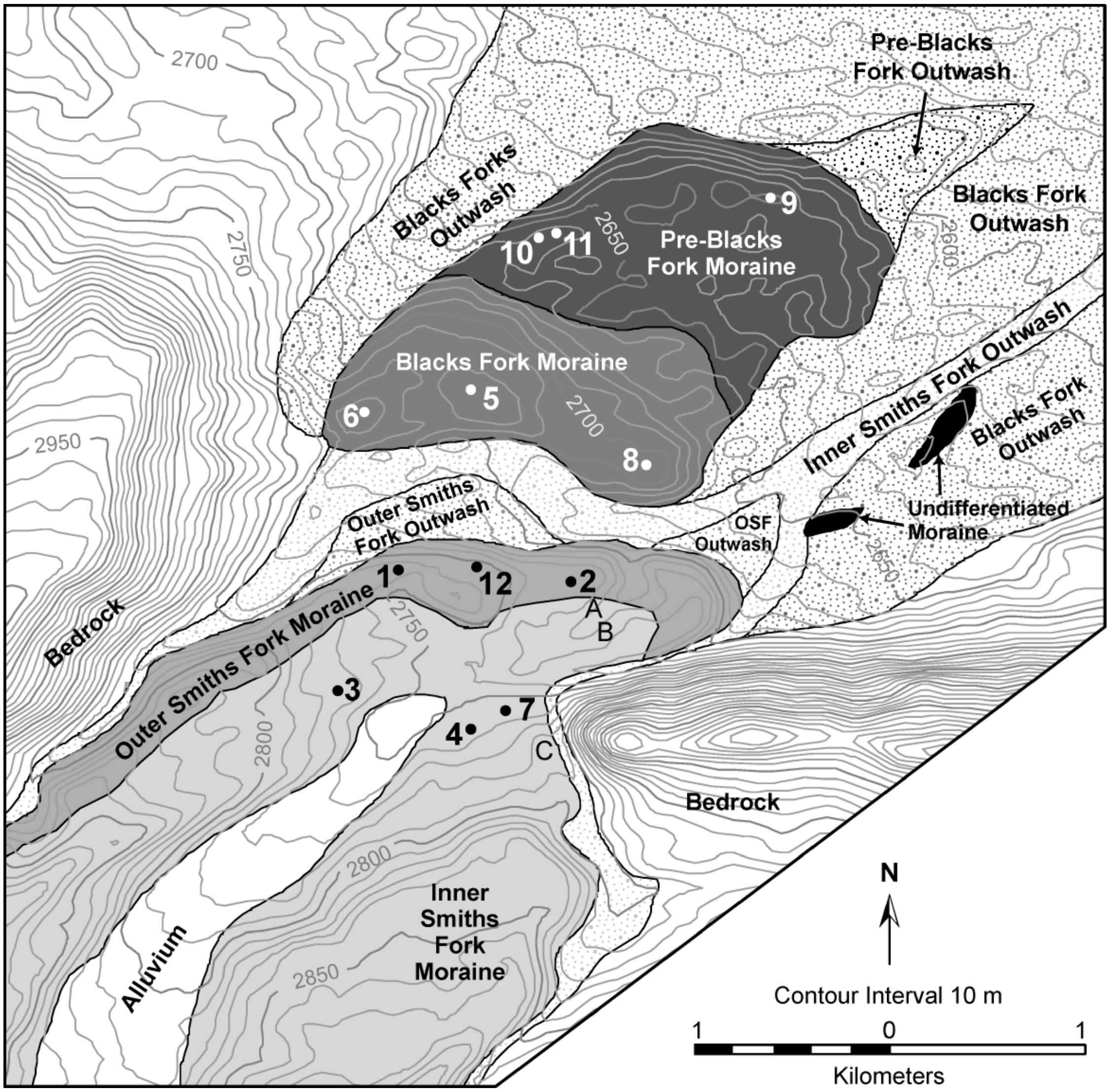

FIGURE 2. Map of Smiths Fork, Blacks Fork, and Pre-Blacks Fork moraines (shaded) and outwash (stippled) in West Fork of Beaver Creek valley. Soil profile locations are shown with bold-faced numbers (Table 1). A, B, and C indicate the location of stream and road cuts where samples of unweathered parent material were collected.

present, (2) between the deposition of the outer and inner Smiths Fork moraines, and (3) between the deposition of the Blacks Fork and outer Smiths fork moraines. The magnitude of the changes during these time periods was determined from the differences between adjacent moraines (we assume zero rind formation and zero clay accumulation for the present). We calculated the rates of clast weathering and soil development for two different age models. In age model #1 we assumed that the outer and inner Smiths Fork moraines were deposited in the early and late phases of MIS-2 (25 and 17 ka, respectively) and that the Blacks Fork moraine was deposited during MIS-6 (140 ka). In age model #2 we assumed that the inner Smiths Fork moraine was deposited in MIS-2 (21 ka), that the outer Smiths Fork moraine was deposited in MIS-4 (64 ka), and that the Blacks Fork moraine was deposited in MIS-6 (140 ka).

STATISTICAL ANALYSIS

A one-way Analysis of Variance (ANOVA) was used to test the significance of observed differences in clast weathering between the moraines. However, we used nonparametric statistical tests to evaluate the significance of differences in soil development. We were not able to establish that the data were normally distributed—a key assumption of most parametric tests—because of the low number of soil excavations on each moraine. Nonparametric tests do not make assumptions about the data distributions and are more reliable when there are few samples per group (Burt and Barber, 1996). We used the Kruskal-Wallis test to examine differences in soil development between all four moraines at once and the Mann-Whitney test to examine the differences between the inner and outer Smiths Fork soil properties. We considered p-values between 0.10 and 0.05 to be marginally significant and those lower than 0.05 to be significant.

Results

MAPPING

We mapped the moraines in the West Fork of Beaver Creek as Pre–Blacks Fork, Blacks Fork, and Smiths Fork moraines (Fig. 2). The two outer moraines are broad crests that average 50 m tall and 350 m wide, and have widely spaced closed

TABLE 1

Soil Profile Descriptions.

Horizon	Depth (cm)	Boundary	Color		Soil Texture				Structure	Consistence		Roots	Coarse Fragments			Clay Skins	pH	Organic Carbon (%)
			Moist	Dry	S	Si	Cl	Class		Moist	Wet		St.	Cob.	Grav.			
Inner Smiths Fork																		
Profile 3																		
Oi	0–2	AW	10YR2/1	10YR3/2	—	—	—	—	—	—	—	—	10	10	10	—	5.0	27.0
Oe	2–4	AW	10YR5/3	10YR3/2	—	—	—	—	—	—	—	—	10	10	15	—	5.0	24.7
EA	4–9	CW	10YR6/3	10YR6/2	68	26	6	SL	1vfsbk	vfr	SO/PO	1vc,2c,m,1f	5	5	15	—	5.1	1.5
E	9–18	CW	10YR6/4	10YR8/2	68	27	5	SL	1vfsbk	vfr	SO/PO	1c,m,f	10	5	15	—	5.2	0.2
Bw1	18–42	CW	7.5YR5/4	10YR7/3	89	7	4	S	1fsbk	vfr	SO/PO	1m,f	10	15	20	—	5.5	0.1
Bw2	42–77	GW	7.5YR4/3	7.5YR7/3	68	28	4	SL	1fsbk	vfr	SO/PO	1c,m	10	10	20	—	6.0	0.2
Bw3	77–150+	—	7.5YR4/4	7.5YR7/2	78	18	4	LS	1fsbk	vfr	SO/PO	1m,f	10	10	20	—	6.2	0.1
Profile 4																		
Oi	0–1	AW	10YR2/1	10YR3/2	—	—	—	—	—	—	—	2f,vf	0	5	15	—	5.3	13.7
Oe	1–3	AW	10YR2/1	10YR3/2	—	—	—	—	—	—	—	2f,vf	0	5	15	—	5.3	13.7
A	3–7	AW	10YR4/2	10YR5/3	68	26	6	SL	1fgr	vfr	SO/PS	1c,m 2f,vf	0	5	15	—	5.7	2.1
E	7–25	CW	10YR6/3	10YR8/2	76	20	4	LS	1fsbk	vfr	SO/PO	1c,m,f	0	7	15	—	5.3	0.1
Bw1	25–46	CW	7.5YR5/3	10YR7/3	77	23	0	LS	1msbk	vfr	SO/PO	1m,f	0	7	15	—	5.6	0.2
Bw2	46–142+	—	7.5YR5/4	10YR7/3	82	18	0	LS	2msbk	fr	SO/PO	1m,f	20	7	10	—	5.8	0.1
Profile 7																		
Oi	0–3	AW	10YR2/1	10YR3/2	—	—	—	—	—	—	—	—	15	10	0	—	-	-
A	3–11	AW	7.5YR4/3	10YR5/3	67	26	7	SL	2fsbk	fr	SO/PS	2vc,1c,m,f,vf	15	10	5	—	6.0	0.6
E	11–15	CW	10YR5/3	10YR7/3	68	32	0	SL	1fsbk	vfr	SO/PO	1c,m,f	15	10	5	—	5.7	0.2
2E	15–29	CW	10YR6/3	10YR8/2	76	24	0	LS	1fsbk	vfr	SO/PO	1f,vf	15	10	20	—	5.6	0.2
2Bw	29–48	CW	10YR5/4	10YR7/3	75	21	4	LS	1fsbk	vfr	SO/PO	1f,vf	15	10	25	—	6.2	0.2
3BC	48–152+	—	7.5YR4/4	7.5YR6/3	90	7	3	S	1fsbk	vfr	SO/PO	1m,f,vf	0	5	10	—	6.2	0.0
Outer Smiths Fork																		
Profile 1																		
Oi	0–1	AW	10YR2/1	10YR3/2	—	—	—	—	—	—	—	—	7	10	10	—	5.6	21.0
Oe	1–4	AW	10YR2/1	10YR3/2	—	—	—	—	—	—	—	—	7	10	10	—	5.6	21.0
A	4–10	CW	10YR4/3	10YR6/2	67	24	9	SL	1msbk	vfr	SO/PO	1c,m,f,2vf	7	10	15	—	5.9	1.7
E	10–16	CW	7.5YR5/3	10YR8/2	61	34	5	SL	1fsbk	vfr	SO/PO	1c,m,f,2vf	5	10	15	—	5.5	0.2
Bw	16–71	CW	7.5YR4/3	7.5YR7/3	72	24	4	SL	2msbk	fr	SO/PO	1c,m,f	15	10	15	—	5.2	0.2
Bt/Bw	71–150+	—	5YR4/3/7.5YR4/3	5YR6/3	71	20	9	SL	2msbk/1fsbk	fr/vfr	SS/PS/SS/PS	1c,m,f	15	10	15	—	5.7	0.3
Profile 2																		
A	0–8	AW	7.5YR4/4	7.5Y6/3	67	27	6	SL	2msbk	fr	SO/PS	1f,vf	0	10	15	—	5.8	0.6
2Bw	8–21	CW	7.5YR4/4	7.5YR6/3	70	23	7	SL	1fsbk	vfr	SO/PO	2m, 1f,vf	10	15	15	—	5.3	0.3
2Bt	21–58	AW	5YR4/3	5YR6/3	55	31	14	SL	2csbk	fi	SS/P	1m,f,vf	20	10	15	1,d,po	5.6	0.2
2BC	58–133+	—	7.5YR4/4	7.5YR6/3	91	3	6	S	1msbk	vfr	SO/PO	1m,f	15	15	15	—	6.1	0.1
Profile 12																		
Oi	0–3	AW	10YR2/1	10YR3/2	—	—	—	—	—	—	—	1f,vf	15	10	10	—	4.9	31.5
A	3–7	AW	10YR3/2	10YR5/3	77	18	5	LS	2fsbk	fr	SO/PO	1m,f,vf	15	15	10	—	5.9	0.7
E	7–26	CW	10YR5/4	10YR7/2	71	25	4	SL	1fsbk	vfr	SO/PO	1vc,c,m,f,vf	10	15	15	—	5.1	0.4
Bw1	26–78	CW	7.5YR5/4	10YR6/3	82	16	2	LS	1msbk	fr	SO/PO	1c,m,f	10	20	15	—	5.6	0.2
Bw2	78–132+	—	7.5YR4/4	7.5YR6/3	89	9	2	S	1msbk	vfr	SO/PO	1f	15	15	5	—	5.9	0.1
Blacks Fork Moraine																		
Profile 5																		
Oe	0–3	AW	10YR2/1	10YR3/2	—	—	—	—	—	—	—	—	10	15	5	—	5.0	19.8
A1	3–9	AW	10YR3/2	10YR5/2	68	27	5	SL	1fgr	vfr	SO/PO	1f, 2vf	10	15	5	—	6.2	1.9

(continued)

TABLE 1

(continued)

Horizon	Depth (cm)	Boundary	Color Moist	Color Dry	Soil Texture S	Si	Cl	Class	Structure	Consistence Moist	Wet	Roots	Coarse Fragments St.	Cob.	Grav.	Clay Skins	pH	Organic Carbon (%)
A2	9–19	CW	7.5YR4/3	10YR7/3	64	33	3	SL	1fsbk	vfr	SO/PO	1c,m,f,vf	10	15	5	—	5.1	0.6
2Bw	19–50	CW	7.5YR4/3	7.5YR6/3	67	28	5	SL	2msbk	fr	SO/PS	1f, 2vf	5	15	15	—	5.9	0.1
2Bt	50–90	AW	5YR4/3	5YR5/4	64	25	11	SL	1fsbk	fr	SS/PS	1m,f	15	10	20	2,d,pf	6.4	0.2
3Bw	90–103	AW	7.5YR4/4	5YR6/3	89	11	0	S	sg	lo	SO/PO	1m	0	2	5	—	6.4	0.1
3Bt	103–141+	—	5YR4/3	5YR5/4	61	26	13	SL	2msbk	fr	SS/PS	1m,f	0	5	10	2,d,pf	6.7	0.2
Profile 6																		
Oe	0–1	AW	10YR2/1	10YR3/2	—	—	—	—	—	—	—	1f, 2vf	5	10	10	—	—	—
A1	1–6	AW	10YR3/1	10YR5/3	64	28	8	SL	1fgr	vfr	SO/PO	2f,vf	7	10	15	—	6.1	1.6
A2	6–19	CW	10YR4/3	7.5YR6/3	70	28	2	SL	1fsbk	vfr	SO/PO	1m	7	10	15	—	6.0	0.2
2Bw	19–101	CW	7.5YR4/3	7.5YR6/3	73	25	2	LS	1fsbk	vfr	SO/PO	1c, 2m,f	0	15	20	—	6.1	0.1
2Bt	101–149+	—	5YR4/4	5YR5/3	77	18	5	LS	2msbk	fr	SS/PS	1m,f	0	15	25	1,d,pf	6.2	0.1
Profile 8																		
Oi	0–1	AW	10YR2/1	10YR3/2	—	—	—	—	—	—	—	—	10	10	0	—	4.9	36.0
A1	1–6	CW	7.5YR3/2	10YR6/3	71	23	6	SL	1fsbk	vfr	SO/PS	1m,f,vf	10	15	10	—	5.8	0.7
A2	6–15	CW	10YR4/3	10YR7/3	66	29	5	SL	1fsbk	vfr	SO/PS	1,m,f	10	15	10	—	5.7	0.6
2Bw	15–32	CW	7.5YR4/3	7.5YR6/3	71	24	5	SL	2msbk	fr	SO/PO	1c,m,f	0	15	15	—	5.4	0.2
2Bt	32–51	AW	7.5YR4/3	7.5YR7/2	70	25	5	SL	2msbk	fr	SS/PS	1m,f	0	15	15	—	5.9	0.2
3Bt	51–63	AW	7.5YR4/4	7.5YR6/3	75	21	4	LS	1msbk	vfr	SS/PS	1m,f	0	5	5	—	6.1	0.1
4Bt	63–144+	—	7.5YR4/3	5YR6/3	74	20	6	SL	1msbk	fr	SS/PO	1m,f	0	15	35	—	6.4	0.3
Pre-Blacks Fork Moraine																		
Profile 9																		
A	0–9	AW	7.5YR3/2	7.5YR4/3	70	22	8	SL	2msbk	fr	SO/PS	2f,vf	0	15	10	—	5.9	1.8
2A	9–31	CW	7.5YR4/3	7.5YR6/3	67	27	6	SL	2msbk	vfr	SO/PS	1m,2f,1vf	5	15	20	—	6.2	0.4
2Bw	31–57	CW	7.5YR4/3	7.5YR6/3	65	30	5	SL	2msbk	fr	SO/PS	1m,f	15	15	25	—	6.5	0.2
2Btk	57–72	CW	5YR4/4	7.5YR5/4	78	15	7	LS	2msbk	fr	SS/PO	1f	15	15	25	—	7.9	0.2
3Bw	72–89	CW	7.5YR4/4	5YR5/4	90	8	2	S	1msbk	vfr	SO/PO	1f	15	5	10	—	7.5	0.1
4Bt	89–150+	—	5YR4/4	5YR4/4	74	15	11	SL	2msbk	fr	S/PS	1f	10	15	20	—	7.8	0.1
Profile 10																		
Oi	0–1	AW	10YR2/1	10YR3/2	—	—	—	—	—	—	—	—	5	20	10	—	5.3	28.5
Oe	1–4	AW	10YR2/1	10YR3/2	—	—	—	—	—	—	—	2vf,f	5	20	10	—	5.3	28.5
A	4–15	AW	10YR3/3	10YR6/3	71	24	5	SL	1fsbk	vfr	SO/PO	1c,m,2f,vf	25	25	15	—	5.9	1.2
Bw	15–51	CW	7.5YR4/3	7.5YR7/2	78	18	4	LS	2msbk	fr	SS/PO	1m,f	30	25	15	—	6.0	0.2
Bt	51–92+	—	5YR4/4	5YR4/4	63	16	21	SCL	2msbk	fr	S/P	1f	30	25	15	1,d,pf	5.6	0.3
Profile 11																		
Oi	0–2	AW	10YR2/1	10YR3/2	—	—	—	—	—	—	—	—	10	15	5	—	5.9	30.0
A	2–17	CW	10YR3/2	10YR6/3	65	28	7	SL	1vfgr	vfr	SO/PO	1vc,c,2m,f,vf	10	15	10	—	5.8	1.3
2Bw	17–67	CW	7.5YR4/3	7.5YR6/3	79	16	5	LS	2msbk	fr	SS/PO	1m,f	10	15	15	—	6.1	0.1
2Bt	67–119+	—	5YR4/4	5YR6/4	62	23	15	SL	2msbk	fi	S/P	1m,f	25	15	15	1,d,pf	6.1	0.1

Boundary: AW = abrupt wavy, CW = clear wavy, GW = gradual wavy.

Texture: number indicates % clay-sized particles; S = sand, LS = loamy sand, SL = sandy loam, SCL = sandy clay loam.

Moist consistence: lo = loose, vfr = very friable, fr = friable, fi = firm.

Wet consistence: SO = non-sticky, SS = slightly sticky, S = sticky; PO = non-plastic, PS = slightly plastic, P = plastic.

Roots: 1 = few, 2 = common; vf = very fine, f = fine, m = medium, c = coarse, vc = very coarse.

Coarse fragments: Stone = larger than 250 mm, Cobble = 250–64 mm, Gravel = 64–2 mm.

Clay Skins: 1 = few, 2 = common; d = distinct; pf = ped face, po = pore filling.

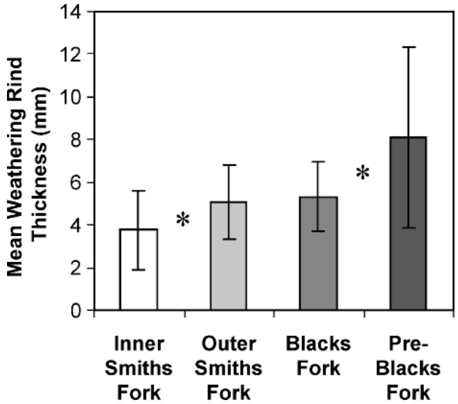

FIGURE 3. Mean weathering rind thickness on each of the four moraines ($n = 50$ for each moraine; error bars depict $\pm 1\sigma$) Asterisks indicate significant differences in rind thickness between the inner and outer Smiths Fork moraines and between the Blacks Fork and Pre–Blacks Fork moraines ($p < 0.001$).

depressions on their surfaces. The Smiths Fork moraine is about 60 m tall, is more hummocky than the two older moraines, and has two crests, hereafter referred to as the inner and outer Smiths Fork moraines. Each moraine is correlated to an outwash surface. Outwash from both Smiths Fork moraines is located in the valley between the Blacks Fork and Smiths Fork moraines. The inner Smiths Fork outwash is incised into the older, outer Smiths Fork outwash about 6 m. Modern streams have incised into the inner Smiths Fork outwash by about 1.5 m.

CLAST WEATHERING

Clast weathering rinds become thicker on the more distal moraines (Fig. 3), indicating relative-age differences among moraines. The differences in rind thickness between the inner and outer Smiths Fork moraines and the Blacks Fork and Pre–Blacks Fork moraines are highly significant ($p < 0.001$). Although the mean rind thickness on clasts from the Blacks Fork moraine is slightly greater than those from the outer Smiths Fork moraine, the difference is not significant.

SOIL DESCRIPTION AND ANALYSIS

Exposures from two stream cuts along the West Fork of Beaver Creek (locations A and B in Fig. 2) and a road cut (location C in Fig. 2) indicate that the moraines consist of two sedimentary units. The upper unit is at least 1.8 m thick in all exposures and is a brown (7.5YR4/4 moist), sandy (93% sand, 6% silt, 1% clay; $n = 2$), loose, and poorly sorted diamicton that is bedded in some exposures. This unit is interpreted as supraglacial sediment. The lower unit is a brown (7.5YR4/4 moist), massive, firm, and very poorly sorted diamicton that has a sandy loam texture (65% sand, 27% silt, 8% clay; $n = 4$). This unit is interpreted as basal till. No sediment of comparable firmness was found in any of the soil pits; therefore we are confident that all of the exposed soil profiles are within the upper supraglacial sediment. We point out that the red colors of the parent material are inherited from the iron-stained Uinta Mountain Group. Accordingly, the average of the two samples collected from the supraglacial units are used as proxies for parent material composition.

Soils on the Smiths Fork moraines commonly exhibit O/A/E/Bw or Bt horizonation (Fig. 2; Table 1). Soils from the Blacks Fork and Pre–Blacks Fork moraines commonly exhibit O/A/Bw/Bt horizonation. The combined thickness of O and A horizons on the Smiths Fork moraines is thinner (average = 8 cm) than that of the Blacks Fork and Pre–Blacks Fork moraines (averages = 15 and 21 cm, respectively). Also, the Blacks Fork and Pre–Blacks Fork moraines lack E horizons. Lithological discontinuities are present in several soil profiles. In all cases these are related to bedding in the supraglacial sediments. We classify all three of the inner Smiths Fork soils and one of the outer Smiths Fork soils as Inceptisols (Cryepts; classification beyond the suborder level is not possible without base saturation measurements); the remaining eight soils are Alfisols (Typic Haplocryalfs; Soil Survey Staff, 2006).

Several PDI parameters show age-related trends (Fig. 4). Rubification, total texture, and moist consistence values all increase with soil age. The clay film PDI parameter increases from the inner Smiths Fork moraine to the outer Smiths Fork moraine, but does not increase further for the oldest two moraines. The average of the rubification, total texture, clay film, and moist consistence PDI parameters (hereafter referred to as average PDI) also increases with moraine age. The higher melanization values on the Pre–Blacks Fork and Blacks Fork moraines are probably not age-related (see discussion). There are significant differences ($p < 0.05$) between some of the moraines for the total texture and moist consistence PDI parameters and marginally significant differences ($p < 0.10$) for the average PDI parameter (Kruskal-Wallis test). There are marginally significant differences ($p < 0.10$) between the inner and outer Smiths Fork moraines for the PDI parameters of rubification, clay films, and moist consistence (Mann-Whitney test).

The profile accumulation of clay-sized particles also increases with age, but there is little difference in the amount of accumulated clay between the Blacks Fork and Pre–Blacks Fork soils (Fig. 5A). The largest difference is between the inner and outer Smiths Fork moraines, but this difference is not significant. The percentage of illuvial clay observed in thin sections of B-horizons shows a similar trend (Fig. 5B). No illuvial clay was observed in the inner Smiths Fork soils, and although there is a large difference in the percentage of illuvial clay between the inner and outer Smiths Fork soils, the differences between the Blacks Fork and Pre–Blacks Fork soils are minimal. The difference in point counts of illuvial clay between the inner and outer Smiths Fork moraine is significant ($p < 0.05$; Fig. 5B).

Two other changes seen in these soils are the accumulation of organic matter, as shown by the Walkley-Black measurements of organic carbon (Table 1) and the melanization PDI parameter (Fig. 4), and the accumulation of silt-sized particles (Fig. 6). These changes appear to be constant across all moraines and to not correlate to soil age.

Calculated rates of clast weathering decrease through time for both age models, but the first age model requires reasonably rapid rind formation during the last glaciation (Table 2). In contrast, rates of soil development are more sensitive to the age model used. For age model #1, the large difference in soil development between the inner and outer Smiths Fork moraines requires rapid soil formation during the last glaciation because of the small age differences between the moraines. This rate is faster than the rate of soil development since the deposition of the inner Smiths Fork moraine (Table 2). For age model #2, the longer time interval between the deposition of the inner and outer Smiths Fork moraines equates to slower soil development. In this age model there is a steady decline in the rates of soil development through time.

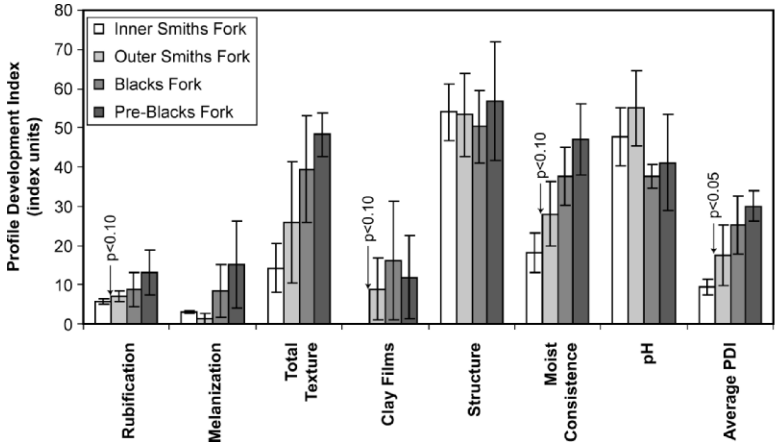

FIGURE 4. Profile development indices for soils on the four moraines (error bars depict $\pm 1\sigma$) "Average PDI" on the far right includes the rubification, total texture, clay films, and moist consistence PDI parameters for each moraine. Significant differences between the inner and outer Smiths Fork moraines are depicted with arrows, with *p*-values specified.

Discussion

MECHANISMS OF SOIL FORMATION

The four dominant mechanisms of soil development in these soils are clay translocation (argilluviation), reddening of the soil (rubification), and the accumulation of organic matter (melanization) and silt-sized particles. The accumulation of clay-sized particles in the subsurface horizons is apparent in the total texture, clay film and moist consistence PDI parameters (Fig. 4), the mass of accumulated clay-sized particles in the soil profiles (Fig. 5A), and the abundance of illuvial clay in soil thin sections (Fig. 5B). It is unlikely that the clay-sized particles are derived from the *in situ* chemical weathering of the parent material because the supraglacial sediment is dominated by quartz, which is resistant to chemical weathering. Therefore, we infer that the clay-sized particles either accumulate directly from eolian deposition, or by deposition of silt-sized particles that subsequently weather to clay (Bockheim and Koerner, 1997; Bockheim et al., 2000).

Although the soil parent material is already quite red (from the iron-stained Uinta Mountain Group), these soils become increasingly red with time as shown by the increase in the rubification PDI parameter (Fig. 4). We assume that the reddening of the soils is related to the accumulation of iron oxides (e.g., Schwertmann, 1993).

All of the soils examined have accumulated organic matter, but we do not believe that the increasing amounts of organic carbon seen in the older soils is an age-related trend because this would only be possible if organic matter were stable for greater than tens of thousands of years. Radiocarbon dating of several soil organic matter fractions in a variety of soils indicate that mean residence times are dependent on several parameters (climate, carbon form, size fraction, soil aggregate stability, etc.), but are on the order of decades to a few millennia (e.g., Trumbore, 2000). Therefore, we believe that the thicker, more organic-rich A-horizons on the Blacks Fork and Pre–Blacks Fork soils are probably the result of less forest and more grassland vegetation on the lower elevation moraines.

These soils have accumulated silt-sized particles, but this does not correlate with soil age (Fig. 6). We propose two possible explanations. First, over many millennia some silt may weather to clay-sized particles that are then translocated in the profile. Second, the silt-sized particles are less likely to be translocated than the clay-sized particles. Because they are retained in near-surface horizons, they may be more susceptible to removal by soil erosion (Hall, 1999). The muted topography of the older moraines indicates that some erosion has occurred. However, we believe that erosion is minimal because of the preservation of closed depressions on the Pre–Blacks Fork moraines. There is no evidence of gullying, so erosion is likely due to creep and therefore only affects the uppermost portion of the soil. As a result we hypothesize that organic matter and silt-sized particles are more likely to be lost from the soil profiles as they are more abundant in the surface horizons, whereas clay-sized particles and iron oxides are more likely to be preserved as they reside in the subsurface horizons. The lowering of the surface of the soils probably causes these weathering products to be leached further into the soil profile.

AGES OF WEST FORK OF BEAVER CREEK MORAINES

We infer the ages of the West Fork of Beaver Creek moraines through correlation to other moraines in the Uinta Mountains and

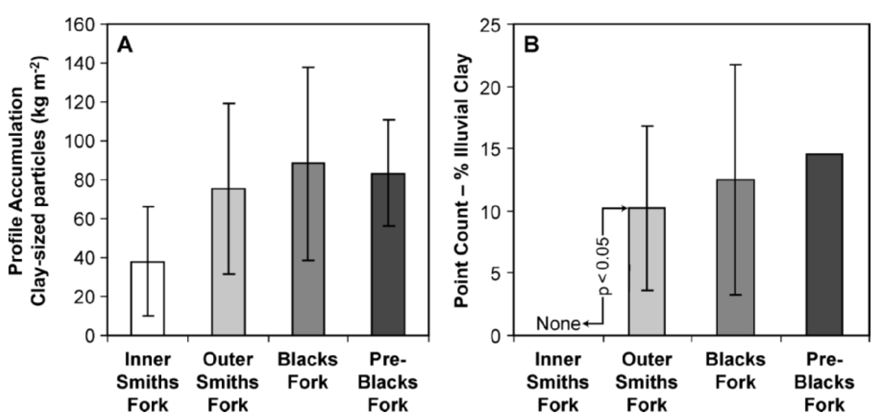

FIGURE 5. Two measurements of the accumulation of clay-sized particles in soils (error bars depict $\pm 1\sigma$) (A) Profile mass accumulation of clay-sized particles. (B) Abundance of illuvial clay in soil thin sections. Only one sample was obtained from Pre–Blacks Fork soils. No illuvial clay was observed in inner Smiths Fork soil thin sections. The difference between the inner and outer Smiths Fork soils is significant ($p < 0.05$).

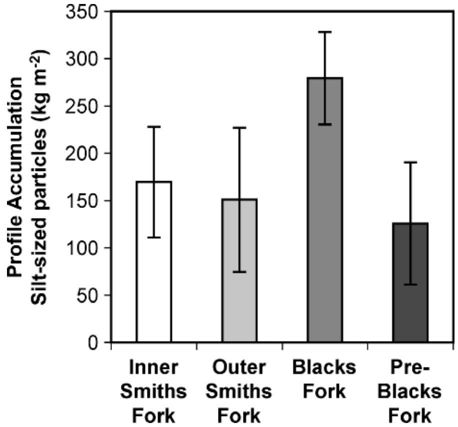

FIGURE 6. Profile mass accumulation of silt-sized particles. There are no age-related trends in this soil development parameter.

in the Wind River Range, 250 km to the north. Bryant (1992) assumed that the Smiths Fork and Blacks Fork glaciations of the Uinta Mountains correlate to the Pinedale and Bull Lake glaciations of the Wind River Range, respectively. Cosmogenic ^{10}Be surface-exposure ages of boulders from various Smiths Fork moraines in the Uinta Mountains have confirmed that the Smiths Fork moraines were deposited during the last glaciation (Munroe et al., 2006). No surface-exposure ages are available for Blacks Fork moraines in the Uinta Mountains, but there is no reason to doubt their correlation to the Bull Lake moraines in the Wind River Mountains.

Although the contrast in clast weathering and soil development between the inner and outer Smiths Fork moraines is certainly related to differences in moraine age, we are unable to quantify this difference. Here we explore the impact of our two age models on the rates of clast weathering and soil development. Age model #1 has both the outer and inner Smiths Fork moraines deposited during early (ca. 25 ka) and late (ca. 17 ka) phases of MIS-2, respectively, whereas age model #2 has the outer Smiths Fork moraine deposited during MIS-4 (64 ka). We point out that the following discussion is not significantly changed if the outer Smiths Fork moraine was deposited during MIS-4 (64 ka), 5b (87 ka), or 5d (108 ka). The age of the Blacks Fork moraines is assumed to be MIS-6 (ca. 140 ka) in both age models.

If age model #1 is correct, then the rate of weathering rind formation between 140 and 25 ka would have been two orders of magnitude less than the rate since deglaciation, and the rate between 25 and 17 ka would have been about 75% of the rate since deglaciation (Table 2). This scenario is plausible. During glacial times, increased effective moisture probably accelerated boulder weathering, but cooler temperatures may have decreased rates. The low rates of boulder weathering prescribed by age model #1 during the last glaciation are reasonable if temperature was the dominant control on weathering rate. Also, the rate of clay accumulation between 140 and 25 ka would have been more than an order of magnitude lower than the rate since deglaciation (between 17 and 0 ka), and the rate between 25 and 17 ka would have been twice the rate since deglaciation (Table 2). Based on our inferences about soil development processes on moraines, elevated rates of clay accumulation during MIS-2 is possible, but the increased amounts of eolian dust probably did not come from the adjacent intermontane basins because wetter basin soils would have prevented eolian processes from entraining dust particles (Dahms and Rawlings, 1996). Instead, the dust might have come from the surrounding outwash plains. Active outwash plains could have supplied large amounts of silt (and perhaps clay-sized particles from the comminution of shale layers in the Uinta Mountain group) to these soils. It is difficult to explain the very low rates of clay accumulation and boulder weathering between MIS-6 and MIS-2 that are required by age model #1.

The similarity of boulder weathering and soil development on the outer Smiths Fork moraine and the Blacks Fork moraine is much more compatible with age model #2. Based on this age model, the rate of boulder weathering was much lower between 140 and 64 ka and between 64 and 21 ka than the rate since 21 ka. A steadily declining rate of boulder weathering after moraine deposition is compatible with rapid breakdown of easily weatherable minerals in the rocks. Also, the rate of clay accumulation between 140 and 64 ka was slightly less than an order of magnitude lower than the rate since 21 ka, and the rate between 64 and 21 ka was about half of the rate since 21 ka. A declining rate of clay accumulation is compatible with minor amounts of soil erosion removing some of the accumulated clay-sized particles.

In the Wind River Range, the soils of the inner Bull Lake moraines are less developed than the outer Bull Lake moraines (Hall and Shroba, 1993, 1995), suggesting that the inner moraines may correspond to a glaciation intermediate in age. However, the most recent chronology for the Bull Lake moraines indicates that all of the Bull Lake moraines were deposited during a single glaciation (Sharp et al., 2003) and that an alternate explanation is needed to account for the differences in soil development. In the West Fork of Beaver Creek, the lack of a robust chronology for these moraines precludes elimination of either of the two age models for the outer Smiths Fork moraine. However, the clast weathering and soil development data are more compatible with preserved MIS-4, 5b, or 5d glacial deposits. The two geochronologic tools most likely to resolve this uncertainty are cosmogenic nuclide surface exposure dating of moraine boulders (e.g., Gosse et al., 1995; Munroe et al., 2006) or uranium-series

TABLE 2

Rates of weathering rind formation and soil development.

	Inner Smiths Fork to Present	Outer Smiths Fork to Inner Smiths Fork	Blacks Fork to Outer Smiths Fork
Age Model #1	17 to 0 ka	25 to 17 ka	140 to 25 ka
Rind Formation (mm kyr^{-1})	0.221	0.165	0.002
Clay Accumulation (kg m^{-2} kyr^{-1})	2.24	4.67	0.11
Average of 4 PDI Parameters (kyr^{-1})	0.56	1.00	0.07
Age Model #2	21 to 0 ka	64 to 21 ka	140 to 64 ka
Rind Formation (mm kyr^{-1})	0.179	0.031	0.003
Clay Accumulation (kg m^{-2} kyr^{-1})	1.81	0.87	0.17
Average of 4 PDI Parameters (kyr^{-1})	0.45	0.19	0.10

disequilibrium dating of pedogenic carbonate rinds in down-valley terraces (e.g., Sharp et al., 2003).

Conclusions

Soil Profile Development Indices, accumulation of organic matter and clay-sized particles, and percentages of illuvial clay in soil thin sections indicate that the four main mechanisms of soil development on terminal moraines in the West Fork of Beaver Creek are argilluviation, rubification, melanzation, and silt accumulation. Both the quantity of clay-sized particles and soil redness generally increase with soil age, but clay accumulation may plateau in the oldest soils. In contrast, the accumulation of organic matter and silt-sized particles do not appear to correlate to soil age. An unexpected finding is a significant difference in both soil development and clast weathering between the inner and outer Smiths Fork moraine crests. It is not clear if the outer Smiths Fork moraine was deposited during an early phase of MIS-2, thus requiring rapid weathering and soil formation during the last glaciation, or if it was deposited during MIS-4, 5b, 5d, necessitating less dramatic changes in weathering and soil-forming rates.

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References Cited

Alexander, E. B., 1989: Bulk density equations for southern Alaska soils. *Canadian Journal of Soil Science*, 69: 177–180.

Anderson, R. S., Repka, J. L., and Dick, G. S., 1996: Explicit treatment of inheritance in dating depositional surfaces using in situ ^{10}Be and ^{26}Al. *Geology*, 24: 47–51.

Atwood, W. W., 1909: Glaciation of the Uinta and Wasatch mountains. U.S. Geologic Survey Professional Paper 61, 96 pp.

Berry, M. E., 1987: Morphological and chemical characteristics of soil catenas on Pinedale and Bull Lake moraine slopes in the Salmon River Mountains, Idaho. *Quaternary Research*, 28: 210–225.

Birkeland, P. W., 1999: *Soil Geomorphology.* 3rd edition*.* Oxford University Press, 430 pp.

Birkeland, P. W., and Burke, R. M., 1988: Soil catena chronosequences on eastern Sierra Nevada Moraines, California, U.S.A. *Arctic and Alpine Research*, 20: 473–484.

Birkeland, P. W., Burke, R. M., and Shroba, R. R., 1987: Holocene alpine soils in gneissic cirque deposits, Colorado Front Range. U.S. Geological Survey Bulletin 1590-E, 21 pp.

Blackwelder, E., 1915: Post-Cretaceous history of the mountains of central western Wyoming, Part III. *Journal of Geology*, 23: 307–340.

Bockheim, J. G., and Koerner, D., 1997: Pedogenesis in alpine ecosystems of the eastern Uinta Mountains, Utah, U.S.A. *Arctic and Alpine Research*, 29: 164–172.

Bockheim, J. G., Munroe, J. S., Douglass, D., and Koerner, D., 2000: Soil development along an elevational gradient in southeastern Uinta Mountians, Utah, USA. *Catena*, 39: 169–185.

Bradley, W. H., 1936: Geomorphology of the north flank of the Uinta Mountains. U.S. Geological Survey Professional Paper 185-I, 163–199.

Bryant, B., 1992: Geologic and structure maps of the Salt Lake City $1^\circ \times 2^\circ$ quadrangle, Utah and Wyoming. U.S. Geological Survey Miscellaneous Investigation Series Map I-1997.

Burke, R. M., and Birkeland, P. W., 1979: Reevaluation of multiparameter relative dating techniques and their application to the glacial sequence along the eastern escarpment of the Sierra Nevada, California. *Quaternary Research*, 11: 21–53.

Burt, J. E., and Barber, G. M., 1996: *Elementary statistics for geographers*. 2nd edition*.* Guliford Press, 640 pp.

Chadwick, O. A., Hall, R. D., and Phillips, F. M., 1997: Chronology of Pleistocene glacial advances in the central Rocky Mountains. *Geological Society of America Bulletin*, 109: 1443–1452.

Colman, S. M., and Pierce, K. L., 1981: Weathering rinds on andesitic and basaltic stones as a Quaternary age indicator, western United States. U.S. Geological Survey Professional Paper 1210, 56 pp.

Coleman, S. M., and Pierce, K. L., 1986: Glacial sequence near McCall, Idaho: weathering rinds, soil development, morphology, and other relative age criteria. *Quaternary Research*, 25: 25–42.

Dahms, D. E., 1993: Mineralogical evidence for eolian contributions to soils of late Quaternary moraines, Wind River Mountains, Wyoming, USA. *Geoderma*, 59: 175–196.

Dahms, D. E., 2004: Relative and numeric age data for Pleistocene glacial deposits and diamictons in and near Sinks Canyon, Wind River Range, Wyoming, U.S.A. *Arctic and Alpine Research*, 36: 59–77.

Dahms, D. E., and Rawlings, C. L., 1996: A two year record of eolian sedimentation in the Wind River Range, Wyoming, USA. *Arctic and Alpine Research*, 28: 210–216.

Douglass, D. C., 2000: Glacial history of the West Fork of Beaver Creek, Uinta Mountains, Utah: M.S. thesis. University of Wisconsin–Madison, 64 pp.

Gee, G. W., and Bauder, J. W., 1986: Particle size analysis. *In* Klute, A. (ed.), *Methods of soil analysis, part 1—Physical and mineralogical methods*. Madison, Wisconsin: Soil Science Society of America, 383–411.

Gosse, J. C., Klein, J., Evenson, E. B., Lawn, B., and Middleton, R., 1995: Beryllium-10 dating of the duration and retreat of the last Pinedale glacial sequence. *Science*, 268: 1329–1333.

Hall, R. D., 1999: Effects of climate change on soils in glacial deposits, Wind River Basin, Wyoming. *Quaternary Research*, 51: 248–261.

Hall, R. D., and Shroba, R. R., 1993: Soils developed in the glacial deposits of the type areas of the Pinedale and Bull Lake glaciations, Wind River Range, Wyoming, U.S.A. *Arctic and Alpine Research*, 25: 368–373.

Hall, R. D., and Shroba, R. R., 1995: Soil evidence for a glaciation intermediate between the Bull Lake and Pinedale glaciations at Freemont Lake, Wind River Range, Wyoming, U.S.A. *Arctic and Alpine Research*, 27: 89–98.

Hansen, W. R., 1965: Geology of the Flaming Gorge area, Utah-Colorado-Wyoming. U.S. Geological Survey Professional Paper 490, 196 pp.

Harden, J. W., 1982: A quantitative index of soil development from field descriptions: examples from a chronosequence in Central California. *Geoderma*, 28: 1–28.

Harden, J. W., and Taylor, E. M., 1983: A quantitative comparison of soil development in four climatic regimes. *Quaternary Research*, 20: 342–359.

Jenny, H., 1941: Factors of soil formation. New York: McGraw-Hill, 281 pp.

Litaor, M. I., 1987: The influence of eolian dust on the genesis of alpine soils in the Front Range, Colorado. *Soil Science Society of America Journal*, 51: 142–147.

McFadden, L. D., Wells, S. G., and Dohrenwend, J. C., 1986: Influences of Quaternary climate changes on processes of soil development on desert loess deposits of the Cima Volcanic Field, California. *Catena*, 13: 361–389.

Muhs, D. R., and Benedict, J. B., 2006: Eolian additions to late Quaternary alpine soils, Indian Peaks Wilderness Area, Colorado Front Range. *Arctic, Antarctic, and Alpine Research*, 38: 120–130.

Muhs, D. R., Crittenden, R. C., Rosholt, J. N., Bush, C. A., and Stewart, K. C., 1987: Genesis of marine terrace soils, Barbados, West Indies; evidence from mineralogy and geochemistry. *Earth Surface Processes and Landforms*, 12: 605–618.

Munroe, J. S., 2005: Glacial geology of the northern Uinta Mountains. *In* Dehler, C. M. (ed.), *Uinta Mountain geology*. Utah Geological Association Publication 33, 215–234.

Munroe, J. S., Laabs, B. J., Shakun, J. D., Singer, B. S., Mickelson, D. M., Refsnider, K. A., and Caffee, M. W., 2006: Latest Pleistocene advance of alpine glaciers in the southwestern Uinta Mountains, Utah, USA: evidence for the influence of local moisture sources. *Geology*, 34: 841–844.

Murphy, C. P., 1986: *Thin section preparation of soils and sediments.* Berkhamsted, AB Academic Press, 149 pp.

Phillips, F. M., Zreda, M. G., Gosse, J. C., Klein, J., Evenson, E. B., Hall, R. D., Chadwick, O. A., and Sharma, P., 1997: Cosmogenic ^{36}Cl and ^{10}Be ages of Quaternary glacial and fluvial deposits of the Wind River Range, Wyoming. *Geological Society of America Bulletin*, 109: 1453–1463.

Reheis, M. C., Sowers, J. M., Taylor, E. M., McFadden, L. D., and Harden, J. W., 1992: Morphology and genesis of carbonate soils on the Kyle Canyon fan, Nevada, U.S.A. *Geoderma*, 52: 303–342.

Reheis, M. C., Goodmacher, J. C., Harden, J. W., McFadden, L. D., Rockwell, T. K., Shroba, R. R., Sowers, J. M., and Taylor, E. M., 1995: Quaternary soils and dust deposition in southern Nevada and California. *Geological Society of America Bulletin*, 107: 1003–1022.

Richmond, G. M., 1965: Glaciation of the Rocky Mountains. *In* Wright, H. E., and Frey, D. G. (eds.), *The Quaternary of the United States*. Princeton, N.J.: Princeton University Press, 217–230.

Schoeneberger, P. J., Wysocki, D. A., Benham, E. C., and Broderson, W. D., 2002: *Field book For describing and sampling soils*. 2nd edition. U.S. Department of Agriculture, 212 pp.

Schwertmann, U., 1993: Relations between iron oxides, soil color, and soil formation. *In* Bigham, J. M., and Ciolkosz, E. J. (eds.), Soil color. Soil Society of America Special Publication 31, 1–69.

Sharp, W. D., Ludwig, K. R., Chadwick, O. A., Amundson, R., and Glaser, L. L., 2003: Dating fluvial terraces by ^{230}Th/U on pedogenic carbonate, Wind River Basin, Wyoming. *Quaternary Research*, 59: 139–150.

Shroba, R. R., 1988: Clay accumulation and soil B horizon development in the Late Pleistocene tills, eastern Uinta Mountains, Utah. American Quaternary Association, Programs and Abstracts, 10th Biennial Conference, p. 152.

Singer, M. J., and Janitzky, P., 1986: Field and laboratory procedures used in a soil chronosequence study. U.S. Geological Survey Bulletin 1648, 49 pp.

Smith, G. I., and Street-Perrott, F. A., 1983: Pluvial lakes of the western United States. *In* Wright, H. E. (ed.), *Late Quaternary environments of the United States*. Vol. 1. University of Minnesota Press, 190–212.

Soil Survey Staff, 2006: *Keys to soil taxonomy*. 10th edition. U.S. Department of Agriculture, 332 pp.

Swanson, D. K., 1985: Soil catenas on Pinedale and Bull Lake moraines, Willow Lake, Wind River Mountains, Wyoming. *Catena*, 12: 329–342.

Trumbore, S., 2000: Age of soil organic matter and soil respiration: radiocarbon constraints on belowground C dynamics. *Ecological Applications*, 10: 399–411.

Zimmer, T. M., 1996: Pedogenesis on quartzite-rich Pleistocene moraines, Smith's Fork Drainage, Uinta Mountains. Masters thesis. University of Utah, 118 pp.

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