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# Properties of Alpine Soils Associated with Well-Developed Sorted Polygons in the Uinta Mountains, Utah, U.S.A.

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## Abstract

Twelve profiles of alpine soils associated with well-developed, but currently inactive, sorted polygons were investigated in the Uinta Mountains of northeastern Utah. The summit upland in the Uintas does not appear to have been glaciated, and these soils are considerably older than those located in lower elevation glacial valleys. Profiles of soils from the polygon centers reveal a dark, organic-rich surface horizon developed in loamy loess overlying a series of redder, sandy B horizons locally exhibiting strongly developed platey structure and pockets of coarser sediment. Irregular and broken horizons at depth reflect extensive cryoturbation during episodes when the sorted polygons are active. Overall morphology and profile quantities of weathering products in these soils are similar to those previously reported for alpine tundra soils in the Uintas; however, the cryoturbated horizons are limited to soils in the patterned ground. A developmental model for these soils emphasizes the combined role of pedogenic processes operating during interglaciations (accumulation of organic matter and loess, translocation of silt and clay, chemical weathering) and periods of cryoturbation (distortion of horizons, redistribution of weathering products within the solum). Outstanding questions include the timing and relative duration of cryoturbation episodes, the timing of loess deposition, and the overall age of the soils.

## Introduction

Alpine soils in the Rocky Mountains have been the subject of considerable scientific attention over the past several decades. Studies focused on these soils have improved our understanding of alpine landscape evolution (Burns and Tonkin, 1982), alpine chronosequences, (Birkeland et al., 1987), postglacial eolian processes (Litaor, 1987; Munn and Spackman, 1990; Dahms, 1993), weathering rates (Thorn et al., 1989; Clow and Drever, 1996), and the distribution of mountain permafrost (Bockheim and Burns, 1991). Alpine soils are also of interest for the role they play in cycling anthropogenic atmospheric nitrogen deposition (Baron et al., 2000; Fenn et al., 2003) and buffering acidic precipitation (Litaor, 1988).

Alpine soils are common in the Rocky Mountains (Bockheim and Burns, 1991) and cover a particularly extensive area in the Uinta Mountains of northeastern Utah (Fig. 1). Here, a broad, high elevation (>3400 m), gently sloping (<17°) summit upland, locally known as "the bollies," covers nearly 200 km$^2$, providing a widespread stable surface on which soils can develop (Munroe, 2006). Three aspects of the geologic history of the Uintas are responsible for this unique geomorphology. First, the mountains are the surface expression of a large, doubly plunging anticline, the hinge of which is concordant with the crest of the range (Hansen, 1969). As a result, the sedimentary rock layers underlying the ridgecrest have a nearly horizontal attitude (Atwood, 1909). Second, following uplift in the early Tertiary, a long period of erosion reduced the crest of the Uinta anticline to a relatively flat upland, with gentle slopes leading northward and southward into the adjacent sedimentary basins (Bradley, 1936). Subsequent fluvial erosion locally incised valleys into these slopes but did not substantially dissect the upland. Third, although Pleistocene glaciation in the Uintas was extensive (Atwood, 1909; Laabs and Carson, 2005; Munroe, 2005), ice was only locally confluent over the ridgecrest and interfluves, and in the majority of the glaciated Uintas these zones of confluence were limited to narrow cols (<1 km wide). As a result, the slopes of this upland were not steepened by glacial erosion like those in the Sierra Nevada or the Wind River Range where ridgecrests were inundated by an ice cap.

The surface of the Uinta bollies is mantled by either alpine tundra soils or areas of periglacial patterned ground and felsenmeer. Previous alpine soils investigations in the Uintas (e.g., Bockheim and Koerner, 1997; Bockheim et al., 2000) have focused on the morphology and properties of the tundra soils, but soils associated with the patterned ground on the bollies have not been formally studied. The most common patterned ground form in this environment is sorted polygons (Washburn, 1956; Fig. 2), although stone stripes are found on steeper slopes. The polygons are usually from 1 to 5 m in diameter, with rims up to 2 m wide composed of coarse quartzite blocks up to 1 m in length, some with long axes vertically oriented. The polygon rims, which are often sunken below the polygon centers, are clast-supported and contain no visible soil. In contrast, polygon centers are usually flat and stone free at the surface, and support a dense mat of *Acomastylis rossii* and other alpine plants. Based on the continuity of vegetation in the polygon centers and the degree of lichen cover on stones comprising the polygon rims, most of these features appear currently inactive and must have formed under a more rigorous paleoclimate.




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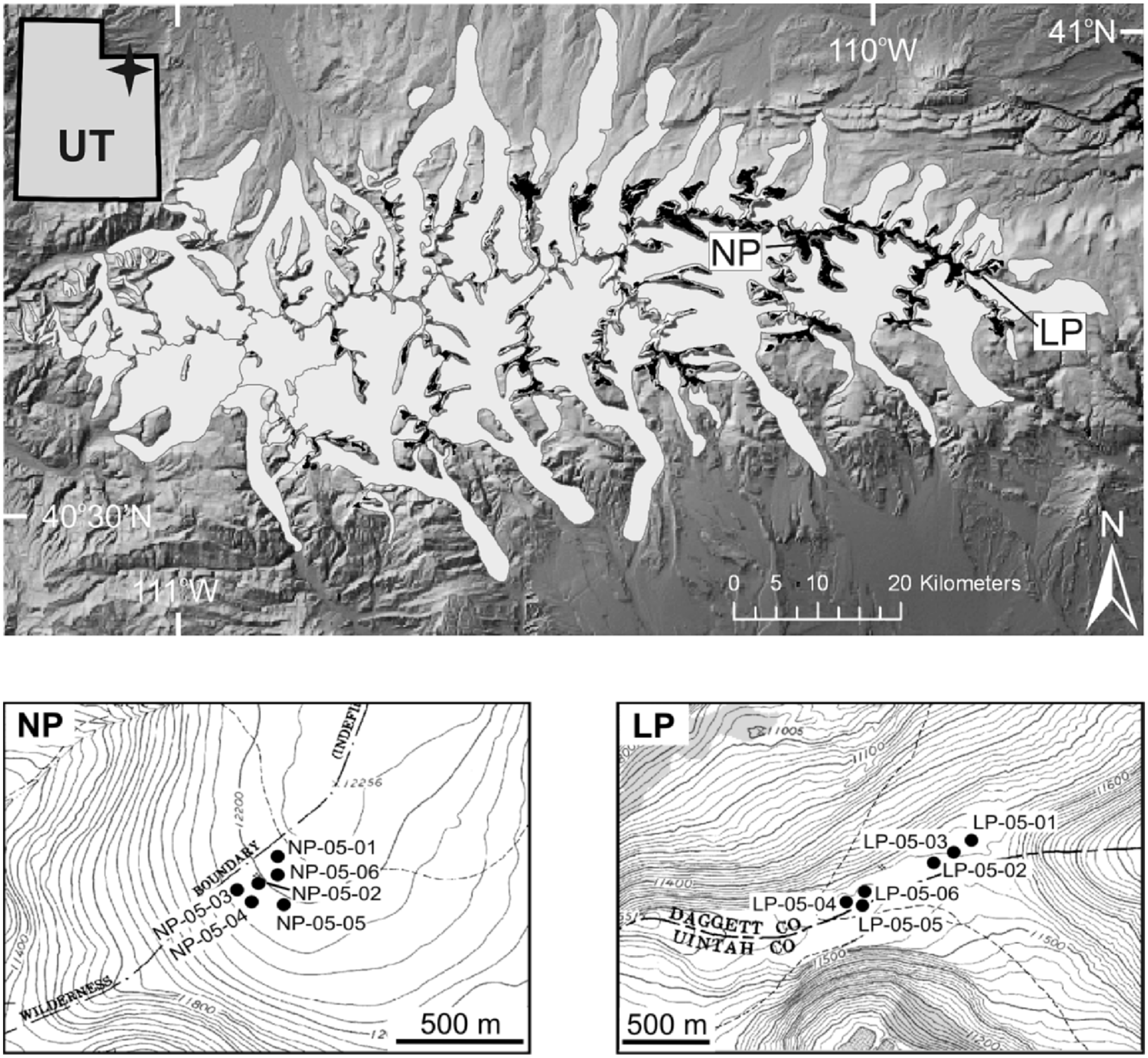


**FIGURE 1. Location of the study area and soil pits. Upper map shows the location of the Uinta Mountains in northeastern Utah (inset), outlines of the valley glacier network in the Uintas during the Last Glacial Maximum (from Munroe and Laabs, unpublished; Refsnider, unpublished), the extent of the bollies (black, from Munroe, 2006), and the locations of the North Pole Pass (NP) and Leidy Peak (LP) study areas. Lower left shows the locations of the NP soil pits; lower right shows the LP study area.**

Because the Uinta bollies were apparently never glaciated (Atwood, 1909; Munroe, 2006), alpine soils there may have persisted through multiple glacial-interglacial cycles, and the soils associated with patterned ground may have endured repeated episodes of cryoturbation interrupted by intervals of relative quiescence. It is interesting to consider, therefore, how the modern form of these soils reflects this complicated history. It is possible that pedogenesis in these soils predominantly occurs during interglacial periods, when warmer temperatures, abundant liquid precipitation, and more extensive vegetation drive a series of pedogenic mechanisms known from lower elevation settings (i.e., melanization, rubification, loess deposition, and argilluviation). During glacial episodes, the soil profile resulting from interglacial pedogenesis might then be destroyed by intense cryoturbation, redistributing weathering products, homogenizing the solum, and essentially resetting the pedogenic clock before the start of the next interglaciation. Alternatively, pedogenesis in this setting may be continually progressive but with different mechanisms dominating under contrasting climatic regimes.

Given the potential antiquity of these soils and questions about their evolution, this study was designed to: (1) investigate the morphology and properties of alpine soils associated with well-developed patterned ground in the Uinta Mountains, (2) to evaluate the relative role of processes operating during glacial and interglacial periods in controlling the properties of the modern soils, and (3) to provide a point of comparison from which to consider the previously reported descriptions of alpine meadow soils in the range.

## Methods

The study area for this project is located in the eastern part of the glaciated Uinta Mountains (Fig. 1). Soil profiles were

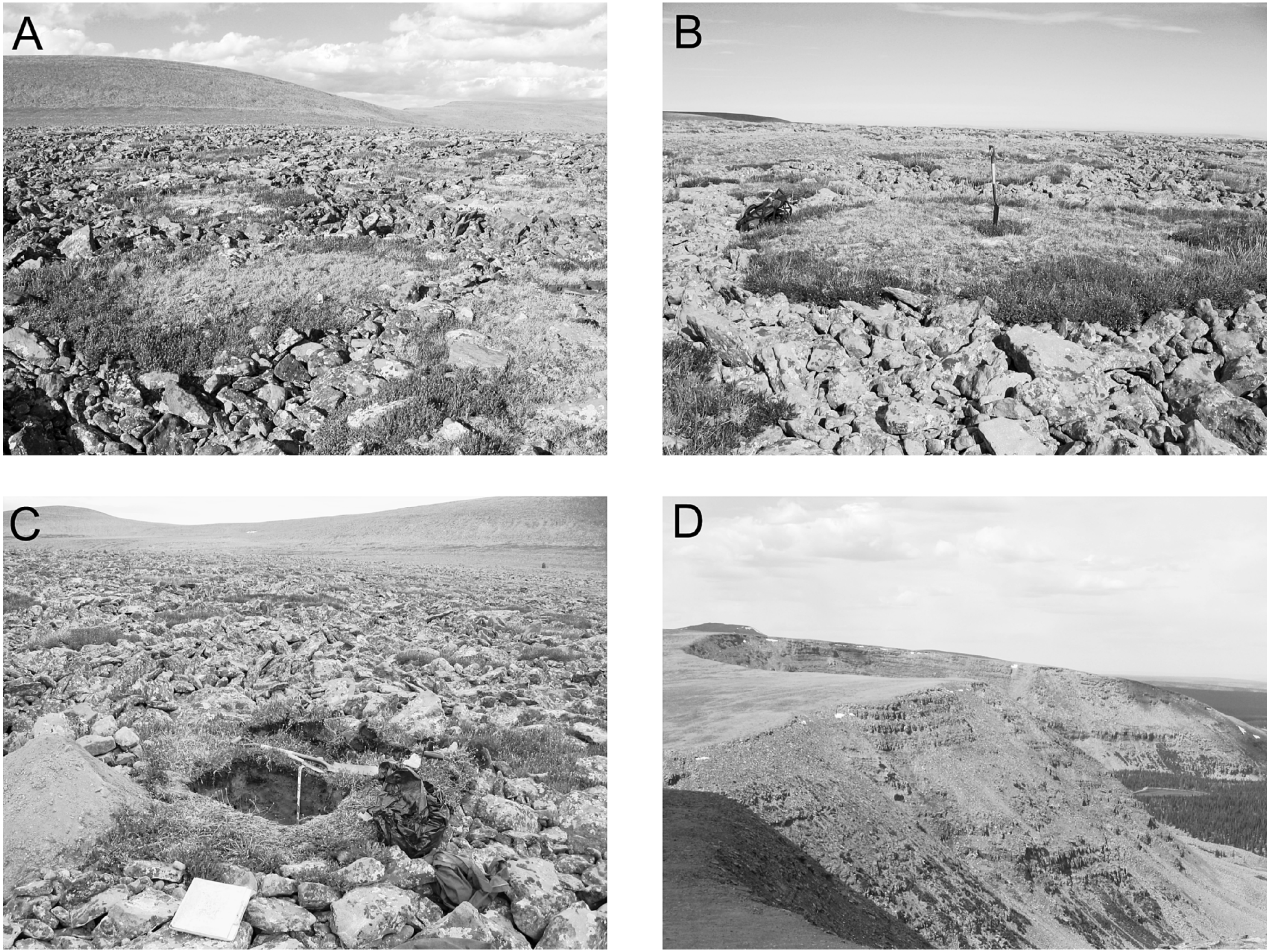


FIGURE 2. (A) Representative sorted polygon at the NP site (location of pit NP-05-2). (B) Representative sorted polygon at the LP site (location of pit LP-05-1), shovel in center of polygon for scale. (C) Excavated soil pit (NP-05-5) revealing a pile of relatively fine soil material excavated from a polygon center in an area of extremely coarse patterned ground. (D) Northern edge of the Uinta bollies near the LP study area showing the flat upland surface abruptly truncated by glacial erosion.

**TABLE 1**

**Locations, properties, and classification of pedons sampled in the Uinta Mountains.**

| Profile | Lat (N) | Long (W) | Elevation (m) | *50 cm temp (°C) | Rooting depth (cm) | Polygon dia. (m) | Taxonomy |
|---|---|---|---|---|---|---|---|
| NP-05-1 | 40°47.913′ | 110°06.655′ | 3735 | 4.4 | 48 | 3 | Typic Dystrocryept |
| NP-05-2 | 40°47.888′ | 110°06.696′ | 3734 | 6.0 | 40 | 3 | Typic Haplocryoll |
| NP-05-3 | 40°47.887′ | 110°06.693′ | 3728 | 6.0 | 65 | 3 | Typic Haplocryoll |
| NP-05-4 | 40°47.896′ | 110°06.685′ | 3732 | 5.0 | 68 | 2 | Humic Dystrocryept |
| NP-05-5 | 40°47.886′ | 110°06.634′ | 3732 | 5.0 | 40 | 3 | Typic Haplocryoll |
| NP-05-6 | 40°47.949′ | 110°06.659′ | 3732 | 6.3 | — | 0.5 | Typic Dystrocryept |
| LP-05-1 | 40°46.01′ | 109°50.946′ | 3518 | 4.2 | 50 | 5 | Humic Dystrocryept |
| LP-05-2 | 40°45.981′ | 109°50.993′ | 3520 | 3.7 | 45 | 5 | Humic Eutrocryept |
| LP-05-3 | 40°45.979′ | 109°51.047′ | 3519 | 3.0 | 55 | 4 | Inceptic Haplocryalf |
| LP-05-4 | 40°45.911′ | 109°51.403′ | 3527 | 3.0 | 45 | 5 | Typic Argicryoll |
| LP-05-5 | 40°45.908′ | 109°51.399′ | 3530 | 2.8 | 42 | 5 | Inceptic Haplocryalf |
| LP-05-6 | 40°45.905′ | 109°51.398′ | 3528 | 3.1 | 73 | 5 | Inceptic Haplocryalf |

* Soil temperatures were determined in early September.

excavated and described at two different sites selected on the basis of their accessibility, geomorphic similarity, and degree of patterned ground development. The first site is on the convex upland called North Pole Pass (hereafter NP) at an elevation of ~3730 m, ~8 km west of Chepeta Lake (U.S. Geological Survey Chepeta Lake 7.5-minute quadrangle). The second site (LP) is located ~22 km east of NP, on the ridgecrest west of Leidy Peak (USGS Leidy Peak 7.5-minute quadrangle) at an elevation of ~3520 m. The arrangement of the six soil profiles studied at each site is shown in Figure 1, and the geographic coordinates of the pits are presented in Table 1.

Soil profiles were described from the centers of sorted polygons with flat, stone-free surfaces. Pits were excavated either to a depth of 100 cm or to an impenetrable stone-rich layer. Stones and cobbles were set aside to inform visual estimates of coarse fragment content. Genetic horizons were identified and physical properties described following standard methodology (Soil Survey Staff, 1993). The soil temperature was taken at a depth of 50 cm immediately after the pit was opened. Bulk samples were taken from each major horizon, and smaller known-volume (15.7 $cm^3$) samples were taken for determination of bulk density. All pits were backfilled.

In the laboratory, samples were dried and passed through a 2-mm sieve. Bulk density was calculated for the known-volume samples at Middlebury College following drying for 24 hrs at 60°C (method 4A3, Soil Survey Staff, 1996). Soil chemistry and particle size distribution for the bulk samples were determined at the University of Wyoming Soil Testing Laboratory (UW-Soiltest, accessed 2007) following methods outlined in the Western States Laboratory Plant, Soil, and Water Analysis Manual (Gavlak et al., 2003). Particle size distribution was determined by hydrometer analysis (method 14.10), pH by saturated paste (1.10), exchangeable bases by ammonium acetate displacement (5.10), CEC by sodium acetate saturation (10.20), and %C and %N were calculated with Micro-Dumas combustion (9.30).

## Results

### *PROFILE MORPHOLOGY*

Soil profiles from the two study areas exhibit a fairly consistent horizonation (Table 2). All of the profiles have a black to dark brown (7.5YR 2.5/1 to 3/2) A horizon, in some cases underlying a thin Oi horizon of undecomposed *A. rossii* leaves and stems. The A horizon has a loam to sandy loam texture, with 16 to 25% clay. Structure is usually moderately developed fine granular or fine subangular blocky. Coarse fragments are rare, although this is somewhat an artifact of the site selection process that was biased towards polygons lacking stones visible at the surface. All but one profile (NP-05-6, which was excavated in an active, unvegetated frost boil) contained a broken A2 horizon, distinguished by a slightly lighter color and higher clay content.

B horizons are considerably redder than A horizons, with colors ranging from brown to reddish brown (7.5YR 4/4 to 2.5YR 4/4). Textures range from loam to loamy sand, with clay contents from 5 to 21% in Bw and Bt horizons respectively. Weak to moderate subangular blocky structures are common, but eight of the twelve profiles contain zones of moderate to strong platey structure. The development of this structure was more dramatic in the NP profiles, but one pit at the LP site (LP-05-1) also encountered platey B horizon material at depth.

Nine of the 12 profiles contained evidence of cryoturbation (Bockheim and Tarnocai, 1998) in the form of broken or irregular horizon boundaries and local sorting by particle size (noted by the suffix jj). These characteristics are quite apparent in Figure 3, which presents sketches of representative profiles of each pedon. Some horizons have been greatly distorted into irregular geometries, and local sand or gravel-rich pockets have formed through sorting processes. No visual evidence of cryoturbation was identified in NP-05-6, which exhibited a uniform soil material from top to bottom. It is possible, however, that focused freeze-thaw activity within this frost boil has completely homogenized the soil, obliterating preexisting horizons.

All profiles (except NP-05-6) exhibit a pronounced textural discontinuity between silty materials at the surface and coarser material at depth. In half of the profiles, the boundary between these two textures corresponds to the break between the Bw and underlying 2Bwjj, 2Btjj, or 2BCjj horizons. In two of the profiles from the LP site, the transition is marked by the boundary between the A1 and the 2A2 horizon.

### *LABORATORY RESULTS*

Most of the laboratory results for these soils exhibit predictable trends with depth (Tables 3 and 4). Bulk densities are lowest in the A1 horizons (generally $<1.00$ g $cm^{-3}$), higher in the A2 horizons (~1.30 g cm$^{-3}$), and highest in the Bt horizons (mean of 1.66 g cm$^{-3}$). A horizons also have the greatest organic carbon content (to 24%), sum of exchangeable bases (to 42 cmol+ kg$^{-1}$), and cation exchange capacity (to 77 cmol+ kg$^{-1}$). All of the pH values are acidic, though they are variable with depth. Nitrogen values are below detection limits in many subsurface horizons, but where calculable the resulting C:N ratios increase with depth. Surface horizons at the NP site have higher carbon content, exchangeable bases, and base saturation than those at the LP site.

### *TAXONOMY*

It is not possible to determine from these excavations if permafrost occurs within 200 cm of the surface at the NP and LP study areas. Thus, it is unclear whether these soils should be classified as Gelisols in U.S. Soil Taxonomy (Soil Survey Staff, 2003). However, given the relatively warm temperatures measured in September at 50 cm (Table 1), these soils are provisionally classified assuming that they lack permafrost within the upper 200 cm. Given this assumption, three different soil orders are represented (Table 1). Three of the 12 profiles classify as Alfisols because they contain evidence of clay translocation, including a Bt horizon and cutans. The Alfisols further classify as Inceptic Haplocryalfs, indicating their cryic thermal regime and argillic horizons less than 35 cm thick. Four of the profiles contain a mollic epipedon and classify as Mollisols. Three of these are Typic Haplocryolls, while the fourth contains an argillic horizon and is a Typic Argicryoll. The remaining five profiles are Inceptisols, classifying as Typic Dystrochrepts ($n$ = 2), Humic Dystrochrepts ($n$ = 2), and a single Humic Eutrochrept, depending on whether they contain an umbric epipedon (denoted by the modifier humic), and whether a horizon between 25 and 75 cm depth has a base saturation in excess of 60% (denoted by the prefix eutr). It should be noted, however, that despite the classification of these 12 profiles into three separate soil orders, the actual differences between them are subtle and classification decisions often turned on slight color or thickness variations in the epipedon.

## Discussion

### *PARENT MATERIALS*

The soil profiles from the study sites contain clear evidence of two parent materials with contrasting textures. All of the deeper pits encountered coarse, quartz-rich sand apparently produced from the underlying sandstone and poorly metamorphosed quartzite by physical weathering. This congelifractate (sensu Bryan, 1946) is overlain by a layer of finer material in an arrangement similar to that reported in studies from other sites in the Rocky Mountains (e.g., Birkeland et al., 1987; Dahms, 1993; Muhs and Benedict, 2006), which concluded that the loamy material is a blanket of alpine loess. In a study of soil properties in different ecoclimatic zones in the Uinta Mountains (upper montane, subalpine, alpine), Bockheim et al. (2000) determined that the average thickness of the loess is not significantly different on surfaces deglaciated in the late Pleistocene and in alpine settings beyond the reach of glacial ice. They concluded, therefore, that the eolian sediment was deposited at some point during the postglacial period, although the exact timing remains unclear. Other studies have concluded that the alpine loess accumulated during the insolation maximum in the early to middle Holocene (Muhs and Benedict, 2006). This interpretation is supported by a lake sediment core from the Colorado Front Range in which the rate of silt accumulation, interpreted to reflect eolian sedimentation, reached a maximum between 8700 and 6300 cal. yrs B.P. (Andrews et al., 1985). During the warmer, more arid climate that prevailed at this time, lowland basins adjacent to the mid-latitude Rocky Mountains supported a sparser vegetation (Fall, 1997), and would have functioned as ideal source areas for loess. Muhs and Benedict (2006) were able to link the alpine loess in their study area to the adjacent lowlands on the basis of mineralogical evidence, and the Uintas are similarly bounded to the north and south by semiarid basins with extensive exposures of fine-grained sedimentary rocks.

### *PEDOGENESIS*

The major pedogenic processes responsible for soil formation in this environment are: (a) organic matter accumulation and melanization, (b) translocation of clay and silt (argilluviation and pervection), (c) rubification, and (d) cryoturbation, which will be discussed separately. Melanization is exhibited by the dramatic contrast in darkness between the surface horizons and deeper parts of the solum. The accumulation of organic matter is encouraged by low temperatures that reduce rates of decomposition and a dominant vegetation type (*A. rossii*) that stores the majority of its biomass belowground. Organic matter is also responsible for the lower bulk density of the surface horizons (Table 4). However, it is worth noting that C:N ratios are generally lowest in the A horizons (Table 4), suggesting that organic matter in this horizon is actually more decomposed than the organic matter present in lower concentrations at greater depths. This situation likely reflects the warmer temperatures and greater oxygenation of the surface horizons during the summer, which may support a larger and more active microbial population.

Clay and silt translocation are exhibited by several features in the soil profiles. Argillic horizons are the most obvious indicator of argilluviation. Clay contents of Bt horizons range up to 21%, in contrast to the sand-dominated Bw and BC horizons (Table 2). Cutans were noted on ped faces in pores in some of the profiles, but they were not abundant. Bt horizons were commonly distorted by cryoturbation, indicating that the formation of these horizons predates the last period of intense frost activity. X-ray diffraction analysis on a Bt horizon sample from the LP site revealed the presence of chlorite, illite, and kaolinite. These minerals may have been produced through weathering of feldspars in the bedrock; however, given the evidence for loess deposition, the majority of the clays are likely of eolian origin. Evidence of pervection includes silt caps (siltans) on the upper surfaces of subsoil clasts (Frenot et al., 1995). Similar features were noted in other Uinta alpine soils (Bockheim et al., 2000) and soils elsewhere in the Rocky Mountains (Burns, 1980; Munn and Spackman, 1990). Individual quartz sand grains were often noted clinging to the underside of larger clasts in the solum.

B horizons are invariably redder than surface horizons, and Bw and Bt horizons generally have redder hues than BC horizons. To an extent, the redness of the Uinta soils is controlled by the reddish-purple color of the underlying bedrock. Analysis of representative samples of Uinta Mountain bedrock by X-ray fluorescence (Munroe, unpublished data) reveals that quartzite layers contain ~1% $Fe_2O_3$, while intercalated shale layers contain up to 7% $Fe_2O_3$. However, the variance in Munsell color within the profile indicates that iron oxides are being concentrated in some horizons, which is likely encouraged by the well-drained nature of these coarse textured soils. It is also notable that the average reddening in the alpine soils, as measured by color development equivalence (Buntley and Westin, 1965), is greater than in soils at lower elevations (Table 5), despite the consistency of parent material color across this elevation range.

Bockheim et al. (2000) emphasized the importance of base cycling in alpine soils in the Uintas, and this process seems to be significant in the soils associated with patterned ground as well. The sum of exchangeable cations (Ca + Mg + K + Na) in these soils is similar to that reported for alpine tundra soils in the Uintas, and is greater than in lower elevation forested soils (Table 5). The amount of exchangeable Ca is also much higher than in the soils of the subalpine forest, reflecting the enhanced Ca-cycling of the *A. rossii* community (Bockheim et al., 2000). The tendency for pH values to be higher in the surface horizons of these soils suggests that eolian sediment is acting as a pH buffer in this system (Table 4). Finally, cation exchange capacity (CEC) is highly correlated with organic matter content in these soils ($r^2 = 0.964$), suggesting that organic matter is an important source of exchangeable cations.

## *CRYOTURBATION*

Irregular horizon boundaries, involutions, and grain size sorting within a profile were all noted by Bockheim and Tarnocai (1998) as evidence of cryoturbation, which is useful for identifying soils affected by permafrost. Given these criteria, it is obvious from the sketches presented in Figure 3 that cryoturbation is a fundamental process in the development of these soil profiles. The presence of these features is not evidence, however, for modern cryoturbation. Indeed, the vegetated polygon centers and apparent stability of stones in the polygon rims (illustrated by the degree of lichen cover) indicate that these features are currently inactive. Therefore, cryoturbation on a scale responsible for the sorted polygons and distorted horizons in the profiles must have occurred under a climate colder than the modern climate—one in which permafrost was present near the surface. Permafrost is not a requirement for cryoturbation, but an ice-rich zone in the subsurface would greatly impede drainage through these soils, enhancing the formation of ice-lenses involved in frost heaving and encouraging cryoturbation on the scale necessary to activate the polygons. Data about the climate of the Uinta alpine zone are sparse, though in 1998 a Remote Automated Weather Station was installed on the ridgeline between the NP and LP sites at an elevation of 3705 m. The mean annual temperature at this station from January 1999 to December 2003 was −2.0°C (Munroe, 2006). Similarly, Bockheim and Koerner (1997) estimated the mean annual soil temperature at 50 cm in an alpine site near LP to be −2.1°C. Thus, the higher elevations of the Uintas should support alpine permafrost. However, despite the presence of gelic materials (Soil Survey Staff, 2003) in most of these profiles, no soil temperatures less than 0°C were encountered during excavation in early September (Table 1). At these temperatures, an active layer more than 1 m thick would be necessary for permafrost to be present in the Uinta alpine zone. Similar situations were noted by Bockheim and Burns (1991) in a survey of pergelic soils in the Rocky Mountains, and Thorn and Darmody (2002) have summarized the difficulties inherent in classifying cold alpine soils within U.S. Soil Taxonomy. Temperature dataloggers, which will provide more information about the thermal regime of the soils studied for this project, were installed in five pits before they were backfilled.

## *COMPARISON WITH OTHER ALPINE SOILS FROM THE UINTAS*

Results reported in previous studies in the Uinta Mountains (Bockheim and Koerner, 1997; Bockheim et al., 2000) allow the soils associated with patterned ground to be compared with alpine tundra soils. Table 5 presents the average values of various soil properties for the soils at the NP and LP sites, along with the means reported for soils of three ecoclimatic zones in the Uintas by Bockheim et al. (2000). Three of the 14 profiles included as "alpine" in their paper were located in patterned ground, but the majority of them were non-sorted soils. In many categories, including color development, solum thickness, and quantities of exchangeable bases and cations, the soils associated with patterned ground are nearly identical to the tundra soils. Soils in polygon centers do appear to have somewhat thicker loess layers, greater profile quantities of fines, and a higher mean organic carbon content, although it is difficult to evaluate the significance of these differences given the small dataset. It appears, therefore, that the major processes responsible for soils forming in the centers of sorted polygons are identical to those operating in the tundra soils. Furthermore, similar to the results obtained by Bockheim et al. (2000), these soils appear to be more weathered than forested soils at lower elevations, as measured by solum thickness and profile quantities of clay. They also have more active base cycling, measured by the sum of exchangeable cations. These differences likely reflect the greater age of the alpine soils, although enhanced rates of weathering in alpine environments have been noted in previous studies (i.e., Birkeland et al., 1987), and recent work in Arctic environments has emphasized the role of chemical weathering under cold climates where physical weathering was previously assumed to be dominant (e.g., Allen et al., 2001; Dixon et al., 2002; Dixon et al., 2004; Darmody et al., 2005; Dixon and Thorn, 2005).

## *DEVELOPMENTAL MODEL*

The evidence reported here allows construction of a developmental model for alpine soils associated with sorted polygons in the Uinta alpine zone. Underpinning the model is a recognition that soils in the non-glaciated alpine zone have evolved over long time periods under the influence of an oscillating Quaternary climate, in contrast to soils on glacial deposits at lower elevations, where pedogenic processes similar to those acting today began operating on a fresh parent material immediately following deglaciation.

(A) During time intervals conducive to cryoturbation, these soils are sorted by freeze-thaw processes, dramatically enhancing preexisting inhomogeneities in the distribution of clasts. The growth of ice lenses during freeze-thaw cycles drives upward and downward translocation that redistributes weathering products within the solum and lateral compression that distorts horizon boundaries. Organic matter may be transported from the surface to deeper levels of the profile by cryoturbation, as is commonly noted in Arctic soils (Bockheim and Tarnocai, 1998). Physical weathering through clast abrasion may also provide mass additions to the sand and silt grain size fractions. The resulting soil profile exhibits strongly contrasting textures, an irregular distribution of organic matter with depth, locally well-developed platey structure, and non-planar horizon boundaries.

(B) During interglacial periods, cryoturbation ceases (or greatly slows), polygon centers become vegetated, and organic matter begins to accumulate at the surface. Eolian sedimentation begins, encouraging the growth of vegetation through the delivery of base cations. The vegetation may also be instrumental in trapping loess through physical

## TABLE 2

**Morphology of alpine soils associated with sorted polygons in the Uinta Mountains.***

| Horizon | Depth (cm) | Thickness (cm) | Bndry** | Cryo*** (%) | Munsell color moist | Texture (% clay) | Structure | | Consistence | | Roots | Coarse Frags. | | | Cutans/ Siltans |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Primary | Secondary | Moist | Wet | | (%St) | (%K) | (%G) | |
| *NP-05-1* | | | | | | | | | | | | | | | |
| Oi | 1–0 | 1 | AS | 0 | — | fibric | — | — | — | — | — | 0 | 2 | 2 | |
| A1 | 0–7 | 4–8 | AI | 0 | 7.5YR 2.5/1 | L 24 | 1fsbk | — | vfr | sl/po | 1c,m,f,v, | 0 | 2 | 2 | |
| A2 | 7–14 | 3–8 | AI | 0 | 7.5YR 4/3 | L 19 | 1fsbk | — | vfr | ss/ps | 1m,f,vf | 0 | 2 | 2 | |
| Bwjj | 14–24 | 5–14 | AI | 50 | 7.5YR 5/4 | L 15 | 2fsbk | 1vfsbk | vfr | ss/ps | 1m,f,vf | 0 | 5 | 2 | |
| 2Bwjj1 | 24–60 | 36 | AI | 100 | 5YR 4/3 | SL 15 | 3fpl | 2fsbk | fr | ss/ps | — | 0 | 5 | 0/20 | |
| 2BCjj | local | 0–10 | AI | 100 | 2.5YR 5/3 | SL 15 | sg | — | lo | so/po | — | 0 | 0 | 0 | |
| 2Bwjj2 | 60–75 | 15+ | — | 100 | 5YR 4/3 | SL 15 | 2msbk | 2fsbk | fi | ss/ps | — | 20 | 5 | 20 | |
| *NP-05-2* | | | | | | | | | | | | | | | |
| A1 | 0–15 | 4–20 | AW | 0 | 7.5YR 2.5/2 | L 20 | 1fgr | 1vfgr | vfr | so/po | 2vf,f 1m | 0 | 2 | 2 | |
| A2 | 0 | 0–15 | AB | 0 | 7.5YR 4/4 | SL 9 | 2fgr | 1vfgr | vfr | so/po | 2vf,f 1m | 0 | 2 | 2 | |
| Bwjj | 15–50 | 0–40 | AI | 100 | 5YR 4/4 | LS 9 | 2msbk | 2fgr | vfr | ss/ps | 1fr,f | 10 | 10 | 10 | |
| 2Bwjj | 50–75 | 10–30 | AI | 100 | 5YR 4/4 | SL 13 | 3mpl | 2msbk | fi | so/po | 1fr,f | 10 | 10 | 10 | |
| 2BCjj | 75–100 | 25+ | — | 100 | 5YR 4/4 | SL 10 | 2msbk | 2fgr | fr | ss/ps | — | 10 | 10 | 10 | |
| *NP-05-3* | | | | | | | | | | | | | | | |
| Oi | 1–0 | 1 | AS | 0 | — | fibric | — | — | — | — | — | 0 | 0 | 5 | |
| A1 | 0–8 | 4–15 | AW | 0 | 7.5YR 2.5/1 | SCL 21 | 1fsbk | 1vfsbk | vfr | so/po | 2fv,f,m | 0 | 0 | 5 | |
| A2 | 8–22 | 0–14 | AB | 50 | 7.5YR 4/3 | SL 14 | 1fsbk | 1vfgr | vfr | so/po | 1vf,f | 0 | 0 | 2 | |
| Bwjj | 22–40 | 10–35 | CW | 100 | 5YR 5/4 | SL 11 | 3fpl | 2vfsbk | fr | ss/ps | 1f,m | 20 | 5 | 5 | |
| 2BCjj1 | 40–65 | 0–40 | AB | 100 | 2.5YR 4/4 | SL 11 | 2fpl | 2fsbk | fr | so/po | 1vf,f | 5 | 10 | 20 | |
| 2BCjj2 | 65–70 | 0–32+ | AB | 100 | 2.5YR 5/4 | SL 14 | 3fpl | 2fsbk | fi | ss/ps | 1f,m | 0 | 0 | 5 | |
| *NP-05-4* | | | | | | | | | | | | | | | |
| Oi | 1–0 | 1 | AS | 0 | — | fibric | — | — | — | — | — | 0 | 0 | 5 | |
| A1 | 0–11 | 6–11 | AW | 0 | 7.5YR 2.5/1 | L 21 | 1fsbk | 1vfgr | vfr | so/po | 1vf,f 2m,c | 0 | 5 | 5 | |
| A2 | — | 0–2 | AB | 50 | 7.5YR 5/3 | — | 1fsbk | 1vfgr | vfr | so/po | — | 0 | 5 | 5 | |
| Bwjj | 11–29 | 9–27 | AW | 50 | 7.5YR 4/4 | L 16 | 1msbk | 2vfgr | fr | ss/ps | 1vf,f,m | 10 | 10 | 10 | siltans |
| 2Bwjj | 29–50 | 0–22 | AB | 100 | 5YR 5/4 | SL 13 | 2fpl | 2fsbk | fi | ss/ps | 1f | 15 | 15 | 20 | siltans |
| 2BCjj | 50–85 | 10–35+ | — | 100 | 5YR 4/4 | SL 15 | 2mpl | 2fsbk | fi | ss/ps | 1f | 15 | 10 | 10 | siltans |
| *NP-05-5* | | | | | | | | | | | | | | | |
| Oi | 1–0 | 1 | AS | 0 | — | fibric | — | — | — | — | — | 0 | 2 | 2 | |
| A1 | 0–5 | 3–10 | CW | 0 | 7.5YR 2.5/1 | L 25 | 1fsbk | 1vfgr | vfr | so/po | 2m 1vf,f | 0 | 2 | 5 | |
| A2 | 5–14 | 5–10 | CW | 0 | 7.5YR 3/4 | LS 8 | 2fsbk | 1vfgr | vfr | so/po | 1vf,f,m | 0 | 2 | 5 | |
| Bw | 14–27 | 10–15 | CW | 0 | 5YR 4/4 | SL 15 | 2msbk | 2fsbk | fr | ss/ps | 1vf,f,m | 20 | 10 | 10 | |
| 2BCjj | 27–56 | 29+ | — | 50 | 2.5YR 4/4 | SL 11 | 3mpl | 2fsbk | fi | ss/ps | — | 20 | 10 | 10 | |
| *NP-05-6* | | | | | | | | | | | | | | | |
| Bw | 0–50 | 50 | — | 100 | 2.5YR 4/4 | L 8 | 2csbk | 2msbk | fi | ss/ps | none | 0 | 0 | 20 | |
| *LP-05-1* | | | | | | | | | | | | | | | |
| Oi | 3–0 | 3 | AS | 0 | — | fibric | — | — | — | — | — | 0 | 2 | 2 | |
| A1jj | 0–6 | 2–13 | AW | 50 | 7.5YR 2.5/2 | SL 16 | 2mgr | 2fgr | vfr | so/po | 2vf, f,m 1c | 10 | 5 | 20 | |
| 2A2jj | 6–24 | 5–18 | AI | 100 | 5YR 3/3 | SL 5 | 2msbk | 2fgr | fr | so/po | 2vf, f 1c | 10 | 5 | 20 | |
| 2Bwjj | 24–46 | 4–22 | AW | 100 | 5YR 4/4 | SL 13 | 1msbk | sg | vfr | so/po | 1vf, f | 30 | 10 | 25 | siltans |

**TABLE 2**
**(continued)**

| Horizon | Depth (cm) | Thickness (cm) | Bndry** | Cryo*** (%) | Munsell color moist | Texture (% clay) | Structure Primary | Structure Secondary | Consistence Moist | Consistence Wet | Roots | Coarse Frags. (%St) | Coarse Frags. (%K) | Coarse Frags. (%G) | Cutans/ Siltans |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2BCjj | 46–80 | 24+ | — | 100 | 5YR 4/3 | SL 9 | 2mpl | 2fpl | fr | ss/ps | 0 | 70 | 10 | 2 | siltans |
| *LP-05-2* | | | | | | | | | | | | | | | |
| A1 | 0–7 | 3–10 | AI | 0 | 7.5YR 2.5/2 | SL 16 | 1msbk | 2vfgr | vfr | so/po | 2vf,f 1m | 0 | 0 | 10 | — |
| A2jj | 7–13 | 0–7 | AB | 100 | 5YR 3/3 | SL 11 | 2fgr | 2vfgr | vfr | so/po | 1f, m | 0 | 0 | 10 | |
| Bwjj | 13–23 | 8–12 | AW | 50 | 5YR 4/3 | SL 15 | 2msbk | 2fgr | fr | ss/ps | 1vf, f | 5 | 5 | 15 | |
| 2Bwjj | 23–52 | 15–50+ | AI | 50 | 5YR 4/4 | SL 15 | 2msbk | 2fsbk | fi | s/p | 1vf, f | 15 | 10 | 10 | |
| 2BCjj | 52–80 | 0–40+ | — | 100 | 5YR 4/6 | SL 10 | 2mpl | 2fsbk | fr | ss/ps | 0 | 20 | 10 | 5 | |
| *LP-05-3* | | | | | | | | | | | | | | | |
| Oi | 3–0 | 3 | AS | 0 | — | fibric | — | — | — | — | — | 0 | 2 | 5 | |
| A1 | 0–14 | 8–14 | AW | 0 | 7.5YR 3/2 | L 22 | 2fsbk | svfgr | vfr | so/po | 2vf, f 1m, c | 0 | 5 | 5 | |
| A2jj | 14–18 | 0–16 | AB | 100 | 7.5YR 4/3 | SL 9 | 2fgr | svfgr | fr | so/po | 1m | 0 | 5 | 5 | |
| 2Bwjj | — | 0–7 | AB | 100 | 5YR 4/4 | LS 8 | 1fgr | sg | vfr | so/po | 0 | 0 | 0 | 2 | |
| 2Btjj | 18–34 | 8–20 | AW | 50 | 5YR 4/4 | L 16 | 2fsbk | 1vfsbk | fr | s/p | 1vf, f, m | 10 | 10 | 10 | 2mkpfpo |
| 2BC | 34–75 | 40+ | — | 0 | 5YR 4/4 | SL 15 | 2mpl | 2vfsbk | fr | ss/ps | 1f | 20 | 15 | 15 | |
| *LP-05-4* | | | | | | | | | | | | | | | |
| A1 | 0–15 | 7–16 | AW | 0 | 7.5YR 2.5/2 | SL 17 | 2fsbk | 2fgr | vfr | so/po | 2vf, f 1m, c | 0 | 0 | 5 | |
| A2 | 15–23 | 8–25 | CW | 0 | 5YR 3/3 | SL 11 | 2fsbk | 2fgr | fr | so/po | 1vs, f, m, c | 0 | 0 | 5 | |
| Bt | 23–55 | 19–32+ | — | 0 | 5YR 4/4 | L 15 | 2fsbk | 2fgr | fr | s/p | 1vf | 15 | 15 | 15 | siltans & 1npfpo |
| *LP-05-5* | | | | | | | | | | | | | | | |
| A1 | 0–5 | 5–40 | AI | 0 | 7.5YR 2.5/2 | L 21 | 1msbk | 2vfgr | vfr | so/po | 2vf, f, m, c | 0 | 0 | 5 | |
| A2jj | 5–25 | 0–20 | AB | 100 | 5YR 4/3 | SL 8 | 2fsbk | 2vfgr | vfr | ss/ps | 1vf, f | 0 | 5 | 5 | |
| Bt | 25–43 | 15–20 | AW | 0 | 5YR 4/4 | L 21 | 2fsbk | 2vfsbk | fr | s/p | 1f | 5 | 10 | 10 | 2mkpfpo |
| BC | 43–60 | 0–17+ | — | 0 | 5YR 4/4 | SL 20 | 2fpl | 2vfsbk | fi | s/p | 0 | 40 | 10 | 5 | |
| 2BCjj | — | 0–40+ | AB | 100 | 5YR 4/4 | SL 10 | 2msbk | sg | fr | ss/ps | 1vf, f | 10 | 10 | 15 | |
| *LP-05-6* | | | | | | | | | | | | | | | |
| A1 | 0–13 | 6–23 | CW | 0 | 7.5YR 2.5/2 | L 21 | 1fsbk | 2fgr | vfr | so/po | 1vf, f, m, c | 0 | 2 | 2 | |
| 2A2 | 13–34 | 15–23 | AW | 0 | 7.5YR 2.5/2 | SL 14 | 2vfgr | sg | vfr | so/po | 2vf, f 1m | 5 | 5 | 20 | |
| 2Bw | 34–57 | 18–30 | CW | 0 | 5YR 4/6 | LS 5 | 2msbk | sg | fr | so/po | 1vf, f, m, c | 10 | 10 | 10 | |
| 2Bt | 57–85 | 25+ | — | 0 | 5YR 4/4 | SL 18 | 2msbk | 2fsbk | fr | s/p | 1vf, f | 15 | 15 | 5 | 2mkpfpo |

* Abbreviations follow Soil Survey Staff (1993).
** Lower Boundary.
*** Cryoturbation.

**TABLE 3**

**Chemical properties of alpine soils associated with sorted polygons in the Uinta Mountains.**

| Horizon | BD (g/cm$^3$) | pH | EC (dS/m) | C (%) | N (%) | C:N | Exchangeable (cmol+/kg) Mg | Ca | Na | K | Sum bases (cmol+/kg) | CEC (cmol+/kg) | BS (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *NP-05-1* | | | | | | | | | | | | | |
| A1 | 0.91 | 5.8 | 0.96 | 12.96 | 1.35 | 9.6 | 5.04 | 24.46 | 0.04 | 1.35 | 30.89 | 54.4 | 57 |
| A2 | 1.42 | 5.4 | 0.17 | 1.37 | 0.12 | 11.4 | 1.75 | 6.88 | 0.03 | 0.30 | 8.96 | 14.9 | 60 |
| Bwjj | 1.46 | 4.8 | 0.24 | 0.56 | 0 | — | 0.88 | 2.78 | 0.03 | 0.02 | 3.71 | 9.6 | 39 |
| 2Bwjj1 | 1.27 | 4.5 | 0.27 | 0.29 | 0 | — | 0.65 | 1.50 | 0.04 | 0.02 | 2.21 | 7.8 | 28 |
| 2BCjj | — | 5.2 | 0.34 | 0.42 | 0 | — | 1.09 | 3.17 | 0.03 | 0.14 | 4.43 | 8.7 | 51 |
| 2Bwjj2 | 1.41 | 4.9 | 0.19 | 0.18 | 0 | — | 0.73 | 1.73 | 0.03 | 0.02 | 2.51 | 6.0 | 42 |
| *NP-05-2* | | | | | | | | | | | | | |
| A1 | 1.02 | 4.9 | 0.19 | 6.28 | 0.61 | 10.3 | 2.97 | 14.41 | 0.04 | 1.45 | 18.87 | 26.6 | 71 |
| A2 | 1.38 | 6.5 | 0.17 | 1.42 | 0.12 | 11.8 | 1.21 | 4.55 | 0.03 | 0.04 | 5.83 | 8.9 | 66 |
| Bwjj | 1.48 | 5.3 | 0.16 | 0.24 | 0.01 | 24.0 | 0.7 | 1.03 | 0.02 | 0.12 | 1.87 | 4.8 | 39 |
| 2Bwjj | 1.46 | 6.3 | 0.18 | 0.43 | 0 | — | 1.22 | 3.21 | 0.03 | 0.12 | 4.58 | 7.3 | 63 |
| 2BCjj | 1.57 | 5.2 | 0.1 | 0.18 | 0 | — | 0.45 | 0.15 | 0.03 | 0.10 | 0.73 | 4.5 | 16 |
| *NP-05-3* | | | | | | | | | | | | | |
| A1 | 0.98 | 6 | 0.62 | 8.10 | 0.75 | 10.8 | 4.02 | 18.70 | 0.04 | 0.61 | 23.37 | 37.8 | 62 |
| A2 | 1.46 | 5.8 | 0.2 | 1.12 | 0.1 | 11.2 | 1.34 | 5.02 | 0.03 | 0.02 | 6.41 | 10.9 | 59 |
| Bwjj | 1.42 | 5.4 | 0.16 | 0.36 | 0.02 | 18.0 | 0.77 | 2.18 | 0.04 | 0.05 | 3.04 | 6.4 | 48 |
| 2BCjj1 | 1.23 | 5.6 | 0.1 | 0.17 | 0 | — | 0.74 | 1.86 | 0.04 | 0.33 | 2.97 | 5.1 | 58 |
| 2BCjj2 | 1.37 | 5.6 | 0.19 | 0.24 | 0 | — | 1.06 | 2.84 | 0.04 | 0.56 | 4.50 | 6.9 | 65 |
| *NP-05-4* | | | | | | | | | | | | | |
| A1 | 0.53 | 5.2 | 1.19 | 23.99 | 1.85 | 13.0 | 7.73 | 30.34 | 0.04 | 2.51 | 40.62 | 77.4 | 52 |
| Bwjj | 1.48 | 4.5 | 0.24 | 1.19 | 0.1 | 11.9 | 0.84 | 3.09 | 0.03 | 0.35 | 4.31 | 14.3 | 30 |
| 2Bwjj | 1.43 | 4.9 | 0.08 | 0.29 | 0.17 | 1.7 | 0.16 | 0.24 | 0.04 | 0.25 | 0.69 | 6.5 | 11 |
| 2BCjj | 1.19 | 4.5 | 0.18 | 0.31 | 0 | — | 0.37 | 1.73 | 0.04 | 0.15 | 2.29 | 8.3 | 28 |
| *NP-05-5* | | | | | | | | | | | | | |
| A1 | 0.83 | 6.3 | 1.07 | 14.74 | 1.32 | 11.2 | 7.48 | 33.53 | 0.04 | 0.83 | 41.88 | 66.1 | 63 |
| A2 | 1.26 | 6.4 | 0.23 | 2.45 | 0.17 | 14.4 | 2.27 | 10.48 | 0.03 | 0.10 | 12.88 | 16.8 | 77 |
| Bw | 1.52 | 6.2 | 0.19 | 0.85 | 0.05 | 17.0 | 1.84 | 6.19 | 0.04 | 0.48 | 8.55 | 12.1 | 71 |
| 2BCjj | 1.43 | 6.2 | 0.12 | 0.23 | 0 | — | 1.14 | 2.71 | 0.04 | 0.41 | 4.30 | 6.6 | 65 |
| *NP-05-6* | | | | | | | | | | | | | |
| 5 | 1.65 | 4.9 | 0.14 | 0.17 | 0 | — | 0.61 | 0.51 | 0.04 | 0.05 | 1.21 | 4.1 | 30 |
| 25 | 1.81 | 4.9 | 0.11 | 0.11 | 0 | — | 0.37 | 0.25 | 0.04 | 0.02 | 0.68 | 5.2 | 13 |
| 50 | 1.73 | 4.6 | 0.2 | 0.14 | 0 | — | 0.32 | 0.31 | 0.03 | 0.25 | 0.91 | 5.5 | 17 |
| *LP-05-1* | | | | | | | | | | | | | |
| A1jj | 1.19 | 4 | 1.04 | 4.45 | 0.43 | 10.3 | 1.4 | 3.21 | 0.15 | 0.54 | 5.30 | 23.2 | 23 |
| 2A2jj | 1.45 | 6 | 0.53 | 0.53 | 0.03 | 17.7 | 0.55 | 0.36 | 0.30 | 0.14 | 1.35 | 3.8 | 36 |
| 2Bwjj | 1.54 | 4.5 | 2.08 | 0.15 | 0 | — | 0.78 | 0.22 | 0.26 | 0.17 | 1.43 | 4.7 | 30 |
| 2BCjj | 1.38 | 4.4 | 0.24 | 0.22 | 0 | — | 0.65 | 0.62 | 0.25 | 0.12 | 1.64 | 3.6 | 46 |
| *LP-05-2* | | | | | | | | | | | | | |
| A1 | 0.92 | 4.6 | 1.18 | 5.69 | 0.53 | 10.7 | 1.66 | 6.84 | 0.18 | 0.50 | 9.18 | 23.0 | 40 |
| A2jj | 1.14 | 4.5 | 0.69 | 2.28 | 0.19 | 12.0 | 1.06 | 2.77 | 0.12 | 0.24 | 4.19 | 12.2 | 34 |
| Bwjj | 1.32 | 4.9 | 0.27 | 0.82 | 0.05 | 16.4 | 1.35 | 2.93 | 0.21 | 0.27 | 4.76 | 9.7 | 49 |
| 2Bwjj | 1.41 | 5.5 | 0.22 | 0.41 | 0.03 | 13.7 | 1.88 | 3.56 | 0.21 | 0.43 | 6.08 | 9.3 | 65 |
| 2BCjj | 1.50 | 5.6 | 0.26 | 0.24 | 0 | — | 1.39 | 1.94 | 0.21 | 0.30 | 3.84 | 6.5 | 59 |
| *LP-05-3* | | | | | | | | | | | | | |
| A1 | 1.24 | 5 | 0.95 | 9.87 | 0.99 | 10.0 | 3.57 | 14.13 | 0.22 | 0.27 | 18.19 | 36.8 | 49 |
| A2jj | 1.44 | 6.1 | 0.32 | 1.69 | 0.16 | 10.6 | 1.66 | 5.34 | 0.17 | 0.15 | 7.32 | 11.4 | 64 |
| 2Bwjj | 1.35 | 5.8 | 0.2 | 0.44 | 0.03 | 14.7 | 0.77 | 1.14 | 0.38 | 0.12 | 2.41 | 4.1 | 59 |
| 2Btjj | 1.40 | 5.6 | 0.3 | 1.68 | 0.13 | 12.9 | 1.62 | 4.69 | 0.16 | 0.20 | 6.67 | 11.1 | 60 |
| 2BC | 1.41 | 4.9 | 0.17 | 0.48 | 0.04 | 12.0 | 1.22 | 2.09 | 0.12 | 0.22 | 3.65 | 7.3 | 50 |
| *LP-05-4* | | | | | | | | | | | | | |
| A1 | 1.00 | 5.3 | 1.58 | 10.63 | 1.06 | 10.0 | 3.35 | 14.18 | 0.18 | 1.30 | 19.01 | 34.5 | 55 |
| A2 | 1.20 | 5.5 | 0.64 | 1.60 | 0.15 | 10.7 | 1.37 | 4.57 | 0.16 | 0.34 | 6.44 | 11.4 | 56 |
| Bt | 1.67 | 4.5 | 0.29 | 0.53 | 0.04 | 13.3 | 0.93 | 0.38 | 0.25 | 0.32 | 1.88 | 7.4 | 25 |
| *LP-05-5* | | | | | | | | | | | | | |
| A1 | 0.88 | 4.8 | 1.2 | 8.31 | 0.86 | 9.7 | 2.42 | 9.14 | 0.26 | 1.23 | 13.05 | 33.2 | 39 |
| A2jj | 1.37 | 5.3 | 0.53 | 1.78 | 0.17 | 10.5 | 1.25 | 2.94 | 0.03 | 0.16 | 4.38 | 10.7 | 41 |
| Bt | 1.66 | 4.9 | 0.22 | 0.67 | 0.06 | 11.2 | 1.54 | 2.31 | 0.43 | 0.30 | 4.58 | 9.4 | 49 |

(continued)

**TABLE 3**

**(continued)**

| Horizon | BD (g/cm$^3$) | pH | EC (dS/m) | C (%) | N (%) | C:N | Exchangeable (cmol+/kg) Mg | Ca | Na | K | Sum bases (cmol+/kg) | CEC (cmol+/kg) | BS (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BC | 1.52 | 4.8 | 0.19 | 0.44 | 0.04 | 11.0 | 1.8 | 2.62 | 0.08 | 0.45 | 4.95 | 8.7 | 57 |
| 2BCjj | 1.38 | 6 | 0.34 | 0.50 | 0.04 | 12.5 | 1.53 | 2.12 | 0.17 | 0.25 | 4.07 | 6.4 | 64 |
| *LP-05-6* | | | | | | | | | | | | | |
| A1 | 0.94 | 4.7 | 0.9 | 7.10 | 0.73 | 9.7 | 2.44 | 8.78 | 0.15 | 1.26 | 12.63 | 30.5 | 41 |
| 2A2 | 0.90 | 5.2 | 0.66 | 3.79 | 0.38 | 10.0 | 1.55 | 3.95 | 0.42 | 0.54 | 6.46 | 17.4 | 37 |
| 2Bw | 1.20 | 6.2 | 0.2 | 0.21 | 0 | — | 0.52 | 0.48 | 0.04 | 0.15 | 1.19 | 2.5 | 48 |
| 2Bt | 1.68 | 5.5 | 0.23 | 0.36 | 0 | — | 1.59 | 1.72 | 0.08 | 0.20 | 3.59 | 7.4 | 49 |

interactions with near-surface winds. The greater abundance of liquid precipitation during interglaciations encourages the translocation of silt and clay into the profile, driving horizon formation in the subsoil. Organic matter that was previously archived at depth by cryoturbation is consumed by microbial activity. The end result is that over the duration of an average interglacial period (~1 × $10^4$ years) the soil becomes strongly differentiated into a series of loamy surface horizons with high organic carbon content and base saturation, and a lower solum of coarser, less-reactive materials locally enriched in translocated iron oxides and clay.

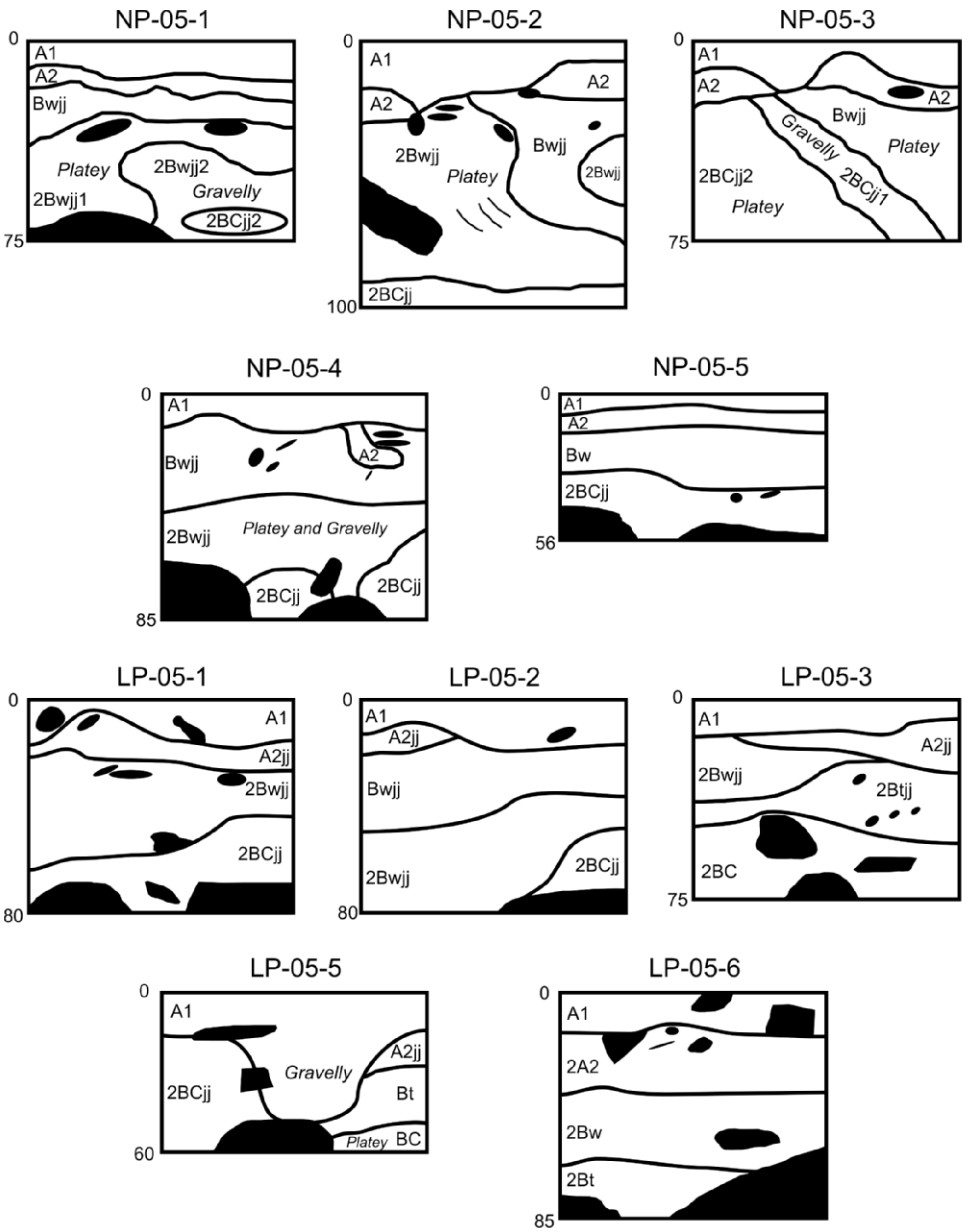


**FIGURE 3. Sketches of 10 of the 12 soil profiles (NP-05-6 was excavated in an active frost boil and lacked horizonation; LP-05-4 was a shallow A1/A2/Bt profile with planar horizon boundaries). Prominent clasts are shown in black, and locations of well-developed structures or strongly contrasting textures are noted. The basal depth of each profile is given (in cm), and each sketch is reproduced at the same vertical scale. Most profiles contain evidence of cryoturbation in the form of broken or irregular horizon boundaries and/or local sorting by particle size.**

**TABLE 4**

**Mean values of various soil properties by horizon.**

| Horizon (n)* | BD (gm/cm$^3$) | pH | EC (dS/m) | C (%) | N (%) | C:N | Exchangeable (cmol+/kg) Mg | Ca | Na | K | Sum bases (cmol+/kg) | CEC (cmol+/kg) | BS (%) | Sand (%) | Silt (%) | Clay (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 (11)** | 0.95 | 5.1 | 0.99 | 10.2 | 1.0 | 10.5 | 3.83 | 16.16 | 0.12 | 1.08 | 21.18 | 40.32 | 50 | 48 | 32 | 20 |
| | *0.19* | *0.7* | *0.36* | *5.5* | *0.4* | *1.0* | *2.14* | *9.73* | *0.08* | *0.63* | *12.08* | *18* | *14* | *11* | *8* | *3* |
| A2 (8)*** | 1.33 | 5.7 | 0.37 | 1.7 | 0.1 | 11.6 | 1.49 | 5.32 | 0.08 | 0.17 | 7.05 | 12.15 | 57 | 61 | 28 | 11 |
| | *0.12* | *0.7* | *0.22* | *0.45* | *0.0* | *1.28* | *0.39* | *2.46* | *0.06* | *0.12* | *2.81* | *2.52* | *14* | *11* | *8* | *4* |
| Bw (6)** | 1.44 | 5.4 | 0.21 | 0.7 | 0.0 | 15.8 | 1.15 | 3.40 | 0.06 | 0.22 | 4.83 | 9.90 | 50 | 57 | 29 | 14 |
| | *0.07* | *0.8* | *0.04* | *0.3* | *0.0* | *2.7* | *0.41* | *1.41* | *0.07* | *0.18* | *1.93* | *3* | *15* | *9* | *8* | *2* |
| Bt (2) | 1.66 | 4.7 | 0.26 | 0.6 | 0.1 | 12.2 | 1.24 | 1.35 | 0.34 | 0.31 | 3.23 | 8.40 | 37 | 48 | 35 | 18 |
| BC (1) | 1.52 | 4.8 | 0.19 | 0.4 | 0.0 | 11.0 | 1.80 | 2.62 | 0.08 | 0.45 | 4.95 | 8.70 | 57 | 59 | 21 | 20 |
| 2A2 (2) | 1.18 | 5.6 | 0.60 | 2.2 | 0.2 | 13.8 | 1.05 | 2.16 | 0.36 | 0.34 | 3.91 | 10.60 | 36 | 71 | 20 | 10 |
| 2Bw (8)** | 1.38 | 5.2 | 0.43 | 0.3 | 0.0 | 13.5 | 0.77 | 1.24 | 0.13 | 0.16 | 2.30 | 5.71 | 40 | 73 | 15 | 12 |
| | *0.11* | *0.6* | *0.67* | *0.1* | *0.1* | *2.80* | *0.49* | *1.09* | *0.14* | *0.13* | *1.65* | *2* | *18* | *8* | *4* | *4* |
| 2Bt (2) | 1.54 | 5.6 | 0.27 | 1.0 | 0.1 | 12.9 | 1.61 | 3.21 | 0.12 | 0.20 | 5.13 | 9 | 54 | 54 | 30 | 17 |
| 2BC (10)** | 1.39 | 5.3 | 0.20 | 0.3 | 0.0 | 12.3 | 0.96 | 1.92 | 0.10 | 0.26 | 3.24 | 6 | 50 | 70 | 19 | 12 |
| | *0.12* | *0.6* | *0.09* | *0.1* | *0.0* | 0.4 | *0.39* | *0.94* | *0.08* | *0.15* | *1* | *2* | *17* | *5* | *4* | *2* |
| fb*** (3) | 1.73 | 4.8 | 0.15 | 0.1 | 0.0 | — | 0.43 | 0.36 | 0.04 | 0.11 | 0.93 | 4.93 | 20 | 45 | 47 | 8 |

* *n* = number of horizons.

** Values in italics present standard deviations for horizons with $n > 3$.

*** Active frost boil.

(C) As the climate cycles back towards conditions encouraging cryoturbation, the vegetative cover will thin, freeze-thaw will begin to disturb the planar horizonation developed during the interglaciations, and eolian sedimentation will slow or cease as effective precipitation increases in the surrounding lowlands.

An important implication of this model is that the evolution of these soils is not solely a result of processes operating today. Instead, the modern form of these soils reflects a complicated history of interactions between pedogenic processes dominant during interglacial periods and a second suite of processes operating during episodes of intense cryoturbation. The two classes could be viewed as examples of progressive and regressive pedogenesis (e.g., Phillips, 1993) in the sense that cryoturbation tends to counter the development of horizons that occurs during interglaciations. However, this simplification would be misleading because cryopedogenic processes are capable of differentiating an initially uniform parent material even in the absence of other pedogenic mechanisms (Bockheim and Tarnocai, 1998).

Despite the usefulness of this model for explaining the history of these soils, questions remain about their evolution. First, because these landscapes were not glaciated, it is difficult to assign an age to the alpine soils, particularly to those associated with patterned ground. Burns and Tonkin (1982) noted that "ridgetop tundra" soils in the southern Colorado Rockies are likely considerably older than 15,000 years, but they were unable to develop a more precise estimate. At the other extreme, research using the concentration of cosmogenic nuclides in the Wind River Range (Small et al., 1999) has determined that alpine regolith is produced at a rate of $\sim$14 m Ma$^{-1}$. Assuming that this rate is applicable in the Uintas, and given that at least some of this material is transported laterally and removed from the alpine zone by slope processes, the regolith in the Uintas, demonstrated in these soil pits to be at least 1 m thick, may have been produced over a period of more than $1 \times 10^5$ yrs, sufficient to span more than one glaciation.

It is also unclear exactly when the period of maximum cryoturbation occurs during the glacial-interglacial cycle. A simple view is that cryoturbation dominates during glacial periods when conditions are colder than modern. Given the relative duration of glacial ($\sim 1 \times 10^5$ yrs) and interglacial ($\sim 1 \times 10^4$ yrs) periods predicted by consideration of the earth's orbital parameters and oceanic records of continental ice volume (Imbrie et al., 1984), this would suggest that the length of time during which these soils are cryoturbating is roughly an order of magnitude greater than the time during which they are static. However, Laabs et al. (2006) concluded from numerical modeling that the mean annual air temperature in the Uintas during the Last Glacial Maximum, ca. 20 ka B.P., was depressed $\sim$6°C below modern values. Thus, the mean annual temperature on the bollies may have been below −8°C, and subfreezing temperatures may have prevailed for all but the warmest summer days. Liquid water may, therefore, have been scarce, and more importantly, the frequency of freeze-thaw events may have been greatly reduced. Thus, cryopedogenic processes on the bollies may have been dramatically slowed, and the high alpine landscape may have become immobilized. Under this scenario, the most opportune time for extensive cryoturbation would be during the slow transition from an interglacial to a glacial period, with a shorter interval during the more rapid deglaciation. A corollary to this theory is that the intervals of active cryoturbation and interglacial soil formation are more equivalent in length. Future work linking realistic climate models to numerical models of patterned ground formation (e.g., Kessler et al., 2001; Kessler and Werner, 2003) would be useful in assessing the validity of these contrasting hypotheses.

## Summary and Conclusion

Soils developed in the centers of sorted stone polygons in the alpine zone of the Uinta Mountains are surprisingly well developed. Sorting processes driven by freeze-thaw have effectively concentrated fine-grained sediment in the polygon centers, producing relatively stone-free soils locally more than 1 m thick. The surface horizons of these soils are developed in a loamy parent material interpreted as alpine loess. Similar sediment has been

TABLE 5

**Properties of soils in different ecoclimatic zones.**

| | This study | Alpine* | Subalpine* | Upper montane* |
|---|---|---|---|---|
| Loess thickness (cm) | 25 | 16 | 16 | 13 |
| Profile silt (Mg/ha) | 2452 | 1823 | 2307 | 2262 |
| A horizon thickness (cm) | 19 | 14 | 9 | 9 |
| **CDE B horizon | 20 | 19 | 12 | 17 |
| Clay, A horizon (%) | 16 | 12 | 6 | 9 |
| Clay, B horizon (%) | 15 | 12 | 4 | 7 |
| Clay ratio (B/A) | 0.9 | 1.1 | 0.6 | 1.5 |
| Solum thickness (CM) | 74 | 73 | 46 | 55 |
| Profile clay (Mg/ha) | 1203 | 936 | 422 | 674 |
| Ca (kmol/ha) | 286 | 312 | 121 | 277 |
| Mg (kmol/ha) | 112 | 81 | 30 | 63 |
| Exch. Bases (kmol/ha) | 435 | 408 | 158 | 352 |
| Exch. Cations (kmol/ha) | 919 | 1004 | 618 | 756 |
| Profile N (mol/m$^2$) | 75 | 112 | 53 | 49 |
| Profile organic C (kg/m$^2$) | 12.0 | 7.7 | 2.4 | 4.6 |

* From Bockheim et al. (2000, Table 2).
** Color Development Equivalence (after Buntley and Westin, 1965).

noted in previous studies of alpine soils in the Uinta Mountains (Bockheim and Koerner, 1997; Bockheim et al., 2000) and elsewhere in the Rocky Mountains (Birkeland et al., 1987; Dahms, 1993; and Muhs and Benedict, 2006). The organic carbon content, base saturation, and cation exchange capacity of the surface horizons are quite high, and are higher in the alpine soils in general than in forested soils at lower elevations. In this regard, the soils in polygon centers are similar to tundra soils found in other areas of the Uinta alpine zone. However, deeper levels of the polygon soils have been greatly impacted by cryoturbation and commonly feature irregular and broken horizons, pockets of coarse, sorted sediment, and strongly developed platey structure. These features are not present in the subsurface of the meadow soils and reflect the operation of cryopedogenic processes when the sorted polygons are active.

Because the alpine upland of the Uinta Mountains was never glaciated, these soils are likely considerably older than those on glacial deposits at lower elevations. Furthermore, because climate has oscillated dramatically during the Quaternary, the modern form of these soils reflects the combined effects of two contrasting suites of pedogenic processes. During interglacial episodes, cryoturbation ceases and loess deposition, the accumulation of organic matter, and silt and clay translocation work to develop a predictable sequence of horizons. During intervals of active cryoturbation, horizons are disturbed, material is sorted by grain size, and weathering products are redistributed. The overall development of these soils requires both sets of processes; a simplistic model in which cryoturbation completely homogenizes the profile and resets the pedogenic clock between interglaciations is inadequate to explain the range of characteristics present in the modern soil profiles.

The results of this study illuminate several important directions for future work. First, the extent of permafrost at high elevations in the Uintas and its role in the development of alpine soils remains unclear. Existing climatological data suggest that permafrost should occur in the Uinta alpine zone; however, the relatively warm temperatures encountered in these soil pits suggest that the active layer is fairly thick. Future work could be aimed at determining the distribution of permafrost in the Uinta alpine zone, perhaps using geophysical techniques (e.g., Hauck et al., 2004), the bottom temperature of snow (BTS) method (Haeberli, 1973), predictive models (e.g., Hoelzle and Haeberli, 1995; Janke, 2005), or a combination of these approaches (e.g., Ishikawa and Hirakawa, 2000).

Second, it is unclear how to determine the age of these soils, both because of a lack of applicable dating methods and uncertainty pertaining to the event that defines their origin. For instance, if the regolith mantling the bedrock in the Uinta alpine zone began forming with the onset of alpine glaciation in the earliest Quaternary, are these soils two million years old? Alternatively, is there some limiting timescale over which the regolith is removed and replenished by slope processes and physical weathering? Continued application of dating techniques based on cosmogenic nuclides (Small et al., 1999), along with numerical modeling of alpine surface processes (Anderson, 2002), offers the best hope for advancing our understanding of these issues.

Finally, it is unknown when the blanket of eolian silt mantling these soils accumulated. Some studies of alpine soils in the Rocky Mountains have suggested that the alpine loess accumulated during the early Holocene (e.g., Andrews et al., 1985; Muhs and Benedict, 2006), but other work has demonstrated that eolian sedimentation is a contemporary process (Thorn and Darmody, 1980, 1985; Dahms and Rawlins, 1996). Given the potential role of eolian processes in the biogeochemistry of the alpine zone, including soil nutrient status (Bockheim et al., 2000) and buffering of surface waters (Litaor, 1988), clarifying the timing of eolian sedimentation in the Uintas and elsewhere in the Rocky Mountains should be a priority for future research.

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## References Cited


Allen, C. E., Darmody, R. G., Thorn, C. E., Dixon, J. C., and Schlyter, P., 2001: Clay mineralogy, chemical weathering, and landscape evolution in Arctic-Alpine Sweden. *Geoderma*, 99: 277–294.

Anderson, R. S., 2002: Modeling the tor-dotted crests, bedrock edges, and parabolic profiles of high alpine surfaces of the Wind River Range, Wyoming. *Geomorphology*, 46: 35–58.

Andrews, J. T., Birkeland, P. W., Harbor, J., Dellamonte, N., Litaor, M., and Kihl, R., 1985: Holocene sediment record, Blue Lake, Colorado Front Range. *Zeitschrift für Gletscherkunde und Glazialgeologie*, 21: 25–34.

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

Baron, J. S., Rueth, H. M., Wolfe, A. M., Nydick, K. R., Allstott, E. J., Minear, J. T., and Moraska, B., 2000: Ecosystem response to nitrogen deposition in the Colorado Front Range. *Ecosystems*, 3: 352–368.

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 1590G, 21 pp.

Bockheim, J. G., and Burns, S. F., 1991: Pergelic soils of the western contiguous United States: distribution and taxonomy. *Arctic and Alpine Research*, 23: 206–212.

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., and Tarnocai, C., 1998: Recognition of cryoturbation for classifying permafrost-affected soils. *Geoderma*, 81: 281–293.

Bockheim, J. G., Munroe, J. S., Douglass, D. C., and Koerner, D., 2000: Soil development along an elevational gradient in the southeastern Uinta Mountains, Utah, U.S.A. *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.

Bryan, K., 1946: Cryopedology, the study of frozen ground and intensive frost-action, with suggestions on nomenclature. *American Journal of Science*, 244: 622–642.

Buntley, G. J., and Westin, F. C., 1965: A comparative study of developmental color in a Chesnut-Chernozem-Brunizem soil climosequence. *Soil Science Society of America Proceedings*, 29: 579–582.

Burns, S. F., 1980: *Alpine soil distribution and development, Indian Peaks, Colorado Front Range*. Ph.D. dissertation. Boulder: University of Colorado, 425 pp.

Burns, S. F., and Tonkin, P. J., 1982: Soil-geomorphic models and the spatial distribution and development of alpine soils. *In* Thorn, C. E. (ed.), *Space and time in geomorphology*. London: Allen and Unwin, 25–43.

Clow, D. W., and Drever, J. I., 1996: Weathering rates as a function of flow through an alpine soil. *Chemical Geology*, 132: 131–141.

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

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

Darmody, R. G., Thorn, C. E., and Allen, C. E., 2005: Chemical weathering and boulder mantles, Kärkevagge, Swedisih Lapland. *Geomorphology*, 67: 159–170.

Dixon, J. C., and Thorn, C. E., 2005: Chemical weathering and landscape development in mid-latitude alpine environments. *Geomorphology*, 67: 127–145.

Dixon, J. C., Thorn, C. E., Darmody, R. G., and Campbell, S. W., 2002: Weathering rinds and rock coatings from an Arctic alpine environment, northern Scandinavia. *Geological Society of America Bulletin*, 114: 226–238.

Dixon, J. C., Thorn, C. E., and Darmody, R. G., 2004: Measuring the extent of chemical weathering in subarctic alpine environments: implications for future research. *Polar Geography*, 28: 63–75.

Fall, P. L., 1997: Timberline fluctuations and late Quaternary paleoclimates in the Southern Rocky Mountains, Colorado. *Geological Society of America Bulletin*, 109: 1306–1320.

Fenn, M. E., Baron, J. S., Allen, E. B., Rueth, H. M., Nydick, K. R., Geiser, L., Bowdman, W. D., Sickman, J. O., Meixner, T., and Johnson, D. W., 2003: Ecological effects of nitrogen deposition in the western United States. *BioScience*, 53: 404–420.

Frenot, Y., Van Vliet-Lanoë, B., and Gloaguen, J. C., 1995: Particle translocation and initial soil development on a glacier foreland, Kerguelen Islands, Subantarctic. *Arctic and Alpine Research*, 27: 107–115.

Gavlak, R., Hornbeck, D., Miller, R., and Kotuby-Amacher, J., 2003: Soil, plant, and water reference methods for the western states region. WCC-103 Publication, WREP-125. (http://cropandsoil.oregonstate.edu/nm/WCC103/Methods/WCC-103-Manual-2003-Table%20of%20Contents-pdf.PDF). Last accessed February, 2007.

Haeberli, W., 1973: Die basis-temperatur der winterlichen schneedecke als möglicher indikator für die verbeitung von permafrost in den aplen. *Zeitschrift für Gletscherkunde und Glazialgeologie*, 1–2: 221–227.

Hansen, W. R., 1969: *The geologic story of the Uinta Mountains* U.S. Geological Survey Bulletin 1291, 144 pp.

Hauck, C., Isaksen, K., Mühll, D. V., and Sollid, J. L., 2004: Geophysical surveys designed to delineate the altitudinal limit of mountain permafrost: an example from Jotunheimen, Norway. *Permafrost and Periglacial Processes*, 15: 191–205.

Hoelzle, M., and Haeberli, W., 1995: Simulating the effects of mean annual air-temperature change on permafrost distribution and glacier size: an example from the Upper Engadin, Swiss Alps. *Annals of Glaciology*, 21: 400–405.

Imbrie, J., Hays, J. D., Martinson, D. G., McIntyre, A., Mix, A. C., Morley, J. J., Pisias, N. G., Pressl, W. L., and Shackleton, N. J., 1984: The orbital theory of Pleistocene climate: support from a revised chronology of the marine $d^{18}O$ record. *In* Berger, A. L., Imbrie, J., Hays, J., Kukla, G., and Saltzman, B. (eds.), *Milankovitch and climate, part 1*. Hingham, MA: D. Riedel Publishing Co., 269–305.

Ishikawa, M., and Hirakawa, K., 2000: Mountain permafrost distribution based on BTS measurements and DC resistivity soundings in the Daisetsu Mountains, Hokkaido, Japan. *Permafrost and Periglacial Processes*, 11: 109–123.

Janke, J. R., 2005: The occurrence of alpine permafrost in the Front Range of Colorado. *Geomorphology*, 67: 375–389.

Kessler, M. A., and Werner, B. T., 2003: Self-organization of patterned ground. *Science*, 299: 380–383.

Kessler, M. A., Murray, A. B., and Werner, B. T., 2001: A model for sorted circles as self-organized patterns. *Journal of Geophysical Research*, 106: 13,287–13,306.

Laabs, B. J. C., and Carson, E. C., 2005: Glacial geology of the southern Uinta Mountains. *In* Dehler, C. M. (ed.), *Uinta Mountain geology*. Salt Lake City: Utah Geological Association, 33, 235–253.

Laabs, B. J. C., Plummer, M. A., and Mickelson, D. M., 2006: Climate during the last glacial maximum in the Wasatch and southern Uinta Mountains inferred from glacier modeling. *Geomorphology*, 75: 300–317.

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.

Litaor, M. I., 1988: Soil solution chemistry in an alpine watershed, Front Range, Colorado, U.S.A. *Arctic and Alpine Research*, 20: 485–491.

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.

Munn, L. C., and Spackman, L. K., 1990: Origin of silt-enriched alpine surface mantles in Indian Basin, Wyoming. *Soil Science Society of America Journal*, 54: 1670–1677.

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

Munroe, J. S., 2006: Investigating the spatial distribution of summit flats in the Uinta Mountains of northeastern Utah, U.S.A. *Geomorphology*, 75: 437–449.

Phillips, J. D., 1993: Progressive and regressive pedogenesis and complex soil evolution. *Quaternary Research*, 40: 169–176.

Small, E. E., Anderson, R. S., and Hancock, G. S., 1999: Estimates of the rate of regolith production using $^{10}$Be and $^{26}$Al from an alpine hillslope. *Geomorphology*, 27: 131–150.

Soil Survey Staff, 1993: *Soil survey manual*. Washington, D.C.: United States Department of Agriculture, Handbook Number 18, 437 pp.

Soil Survey Staff, 1996: *Soil survey laboratory methods manual*. Washington, D.C.: United States Department of Agriculture, Soil Survey Investigations Report 42, v. 3.0, 716 pp.

Soil Survey Staff, 2003: *Keys to soil taxonomy*. Ninth edition. Washington, D.C.: U.S. Department of Agriculture, 332 pp.

Thorn, C. E., and Darmody, R. G., 1980: Contemporary eolian sediments in the alpine zone, Colorado Front Range. *Physical Geography*, 1: 162–171.

Thorn, C. E., and Darmody, R. G., 1985: Grain-size distribution of the insoluble component of contemporary eolian deposits in the alpine zone, Front Range, Colorado, U.S.A. *Arctic and Alpine Research*, 17: 433–442.

Thorn, C. E., and Darmody, R. G., 2002: Permafrost and ground temperature regimes: a challenging soil classification problem in low Arctic and alpine environments. *Geografisk Tidsskrift, Danish Journal of Geography*, 102: 1–9.

Thorn, C. E., Dixon, J. C., Darmody, R. G., and Rissing, J. M., 1989: Weathering trends in fine debris beneath a snow patch, Niwot Ridge, Front Range, Colorado. *Physical Geography*, 10: 307–321.

UW-Soiltest: University of Wyoming Soil Testing Laboratory (http://uwadmnweb.uwyo.edu/RenewableResources/soil/soil_lab.htm). Last accessed February, 2007.

Washburn, A. L., 1956: Classification of patterned ground and review of suggested origins. *Geological Society of America Bulletin*, 67: 823–866.

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