Soils in Granitic Alluvium in Humid and Semiarid Climates along Rock Creek, Carbon County, Montana

U.S. GEOLOGICAL SURVEY BULLETIN 1590–D

Chapter D

Soils in Granitic Alluvium in Humid and Semiarid Climates along Rock Creek, Carbon County, Montana

By MARITH C. REHEIS

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SOIL CHRONOSEQUENCES IN THE WESTERN UNITED STATES

DEPARTMENT OF THE INTERIOR

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FOREWORD

This series of reports, "Soil Chronosequences in the Western United States," attempts to integrate studies of different earth-science disciplines, including pedology, geomorphology, stratigraphy, and Quaternary geology in general. Each discipline provides information important to the others. From geomorphic relations we can determine the relative ages of deposits and soils; from stratigraphy we can place age constraints on the soils. Field investigations and mineralogic and sedimentologic studies provide information on the nature and types of deposits in which soils form. As a result of our work, we have estimated rates of soil formation, inferred processes of soil formation from trends in soil development with increasing age, and obtained information on the types of weathering that occur in various areas. In return, soil development and soil genesis have provided data on the age of landforms, the timing and duration of sedimentation, and, in some cases, the history of climatic fluctuations.

Between 1978 and 1983, a coordinated and systematic study was conducted on soil development in different types of geologic deposits in the Western United States. The goals of this project, led by the late D.E. Marchand and subsequently by M.N. Machette, were to learn whether rates of chemical, physical, and mineralogic transformations could be determined from soil chronosequences; how these rates vary in different mineralogic and climatic environments; and how accurately soils can be used for such problems as estimating the ages of deposits, periods of landscape stability, and timing of fault movements. This series of reports presents data from several soil chronosequences of that project.

More than 100 analyses on more than 1,000 samples were performed on soils collected in the Western United States. Some results have appeared in various books, journals, and maps (for example, Harden and Marchand, 1977, 1980; Burke and Birkeland, 1979; Dethier and Bethel, 1981; Marchand and Allwardt, 1981; Meixner and Singer, 1981; Busacca, 1982; Harden, 1982a, b; Harden and Taylor, 1983; Machette, 1983; Machette and Steven, 1983; Busacca and others, 1984; Machette and others, 1984; Reheis, 1984). In the reports in this series, the basic field information, geologic background, and analytical data are presented for each chronosequence, as well as some results additional to the previous publications.

One of the most significant aspects of these chronosequence studies is that in every study area, many soil parameters change systematically over time, or with the age of deposits. As Deming (1943) emphasized, it is this recurrence of correlation in such different conditions that is most significant to geologic and pedologic studies. In relatively moist areas, such as coastal and central California, such soil properties as percent clay or reddening of soil colors change most systematically over time. In more arid regions, such as in the Bighorn Basin of Wyoming, calcium carbonate and gypsum contents best reflect the relative ages of the deposits. A few parameters—for example, elemental composition of sands or clays—appear to be comparable between areas so diverse in climatic setting.

Numeric age control has enabled us to estimate rates of soil development. In some places, we have been able to compare rates between different areas. For example, in central California, rates of clay accumulation were found to be most rapid during the initial stages of soil development; these rates declined with increasing age. The straightest lines for regression were on a log-log scale. In coastal California, rates of clay accumulation appeared to be much higher than in central California. This difference in rates could be due to parent material (the coastal soils that we studied were formed on reworked shale and sandstone, whereas central California soils were developed in granitic alluvium), and (or) the differences in rates could be due to eolian additions of clay. In the Bighorn Basin of Wyoming, rates of clay accumulation, as well as most other soil properties, increased linearly over time, with no apparent decrease in initial rates.

The data we present here suggest many opportunities for further interpretation. For example, we may learn how climate, vegetation, and mineralogy affect the rates of clay formation or organic-matter accumulation. In some study areas, we present data for rare-earth elements, which could be used to examine how each element reacts in different weathering environments. These examples are only a fraction of the possible future studies that could be conducted on the data presented here.

J.W. Harden
Editor

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Soils in Granitic Alluvium in Humid and Semiarid Climates along Rock Creek, Carbon County, Montana

By Marith C. Reheis

ABSTRACT

Soils formed on glaciofluvial terraces of Rock Creek, southwest of Billings, Mont., yield information on rates of soil development under controlled conditions of parent material, vegetation, and relief. Three chronosequences of soils on seven terraces, which range in age from 7 to 2,000 ka (thousands of years before present), reflect the modern decrease in precipitation with decreasing altitude. Some soil properties indicate paleoclimate and test current models of climate during the last glaciation.

The ages and glaciofluvial origin of the terraces, including, from youngest to oldest, the Holocene (nonglacial), Pinedale, Bull Lake, Boyd, Lower Roberts, Upper Roberts, and Mesa terraces, have been established by using several methods. The dating methods include correlation with dated deposits in West Yellowstone, Mont., tephrochronology, stream-incision rates, and comparison to the marine oxygen-isotope record. The Pinedale and Bull Lake terrace deposits are glaciofluvial because they merge with glacial moraines within the mountains. The Lower Roberts terrace gravel is probably glaciofluvial because it appears to have formed contemporaneously with a pre-Bull Lake till. The glaciofluvial origin of deposits of the Boyd, Upper Roberts, and Mesa terraces is inferred because these gravels resemble in form and thickness those of known glaciofluvial deposits.

Soil properties of total texture, pH, and color, expressed on a numeric scale, show statistically significant correlations with age for all the soils studied. The texture, color, and clay films of soils in the wetter environment at the mountain front develop at logarithmic rates. Soils older than 20 ka from the drier basin climate exhibit linear rates of change with time in pH, color, and texture, but the younger soils appear to develop at logarithmic rates. The pH of mountain-front soils decreases over time, whereas that of drier soils increases. Logarithmic rates of development in mountain soils are probably controlled by near-surface weathering processes, whereas linear rates of development in drier soils may be controlled by influx of eolian dust.

Evidence of permafrost conditions, periodic dissolution of $CaCO_3$ in the drier soils, and depths of pedogenic clay demonstrate a substantial increase in available moisture during glaciations, owing primarily to a decrease of evapotranspiration due to lower temperatures. The soils farthest downstream have $CaCO_3$ morphology that, assuming a 10 $^{\circ}C$ decrease in mean annual temperature, suggests a concomitant decrease in actual precipitation. The changing position of the boundary between calcic and noncalcic soils on each terrace may reflect either increasing wetness of recent interglaciations or soil conditions induced by periodic leaching and precipitation of $CaCO_3$ near the boundary.

INTRODUCTION

Soils formed on the terrace deposits of Rock Creek, which drains the northeastern part of the Beartooth Mountains southwest of Billings, Mont., afford a rare opportunity to study both chronologic and climatic effects on soil development. Most studies to date have concentrated on either chronosequences (Shroba, 1977; Bockheim, 1980; Harden, 1982a and b; Muhs, 1982) or climosequences (Thorp, 1931; Harradine and Jenny, 1958; Netoff, 1977; Harden and Taylor, 1983). A chronosequence consists of soils of different ages developed on the same parent material, under the same climate and vegetation, and under the same conditions of topographic relief, and shows systematic changes of soil properties that can be ascribed to the effects of time alone. Climosequences of soils have developed on parent material of the same age and composition, and under similar vegetation and relief, but in different climates (Jenny, 1941).

The separate effects of time and climate upon soil formation need to be identified in Quaternary studies. Soils are used both to estimate ages of surfaces, in the absence of other age control (Machette, 1978, and Levine and Ciolkosz, 1983), and to indicate paleoclimate at some time during soil formation (Sorenson and others, 1971; Dan and Yaalon, 1971; Rutter and others, 1978). Many soil properties, however, are affected by both time and climate. For example, soils redden with time as iron-bearing minerals weather and release iron to be oxidized in the soil environment. This process is enhanced by increasing temperature, and so red soils are commonly interpreted as having formed during warm climatic episodes. The cumulative effects of weathering over time tend to overwhelm or average the changes in morphology or other properties that may reflect climate in younger soils (Stephens, 1965). Moreover, relatively few soil properties formed under one climate resist alteration when the climate changes (Yaalon, 1971).

A chronosequence of soils is found on seven terraces along Rock Creek extending from the Beartooth Mountains front downstream into the Yellowstone basin. The chronosequence was sampled in the cool, moist environment of the mountain front, in the cool, semiarid basin, and in a transitional climate between these two extremes. These areas are here referred to as three separate chronosequences.

The soil-forming factor of climate cannot be held constant for the time period of the chronosequences, because Quaternary climate has fluctuated. However, if the effects of fluctuating climate can be separated from time-dependent properties, some inferences can be made concerning paleoclimate. The mountain-front chronosequence represents formation under a climate that was periodically cooler and effectively moister than the modern interglacial climate. The basin chronosequence, farthest downstream, has soils that show relatively continuous accumulation of pedogenic[1] calcium carbonate ($CaCO_3$); these soils formed under a semiarid climate that at times was more moist than at present. The transition chronosequence is so named because the soils lie in the zone of transition--close to the calcic-noncalcic soil boundary--between mountain-front soils without pedogenic $CaCO_3$ and basin soils that have $CaCO_3$. Soils in the transition zone have undergone alternate leaching and precipitation of $CaCO_3$. Although soils of the transition chronosequence show field evidence of past climatic fluctuations in the study area, the basin soils preserve better records of such fluctuations.

Interpretations in this paper rely chiefly on field data and micromorphology. Some particle-size and chemical data are used to discuss the parent material and the amount and source of pedogenic $CaCO_3$. Reheis (1984) discussed other laboratory data, including particle size and chemical and mineralogical analyses.

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[1]"Pedogenic" or "secondary" as used in this report refers to soil properties affected by processes of soil formation, including both weathering in situ and additions of eolian dust.

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GEOMORPHIC AND CLIMATIC SETTING

Geomorphic Setting

Rock Creek drains a glaciated portion of the northeastern Beartooth Mountains in Montana (figs. 1 and 2). The stream extends 60 km from the mountain front to the Clarks Fork of the Yellowstone River

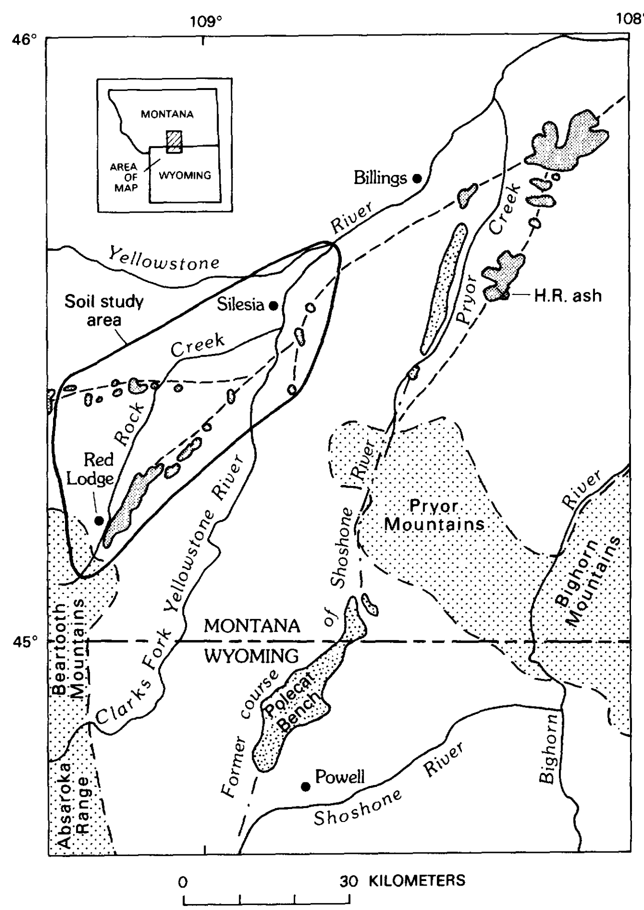


Figure 1. Location of study area in the northern Bighorn Basin, Mont. (modified from Mackin, 1937). H. R. ash is the 2,010-ka Huckleberry Ridge ash. Mesa and equivalent terrace remnants are gray. The Polecat Bench and equivalent terraces of the Shoshone River are stippled. Short dashed lines show drainage pattern at 2,010 ka.

southwest of Billings. The oldest terrace deposited by Rock Creek, Mesa terrace, presently forms the drainage divide between Rock Creek and the Clarks Fork. Terraces in this area commonly occupy positions of topographic prominence and are exceptionally well preserved, because they are underlain by crystalline gravel that is permeable and far more resistant to weathering than the exposed Cretaceous and Tertiary

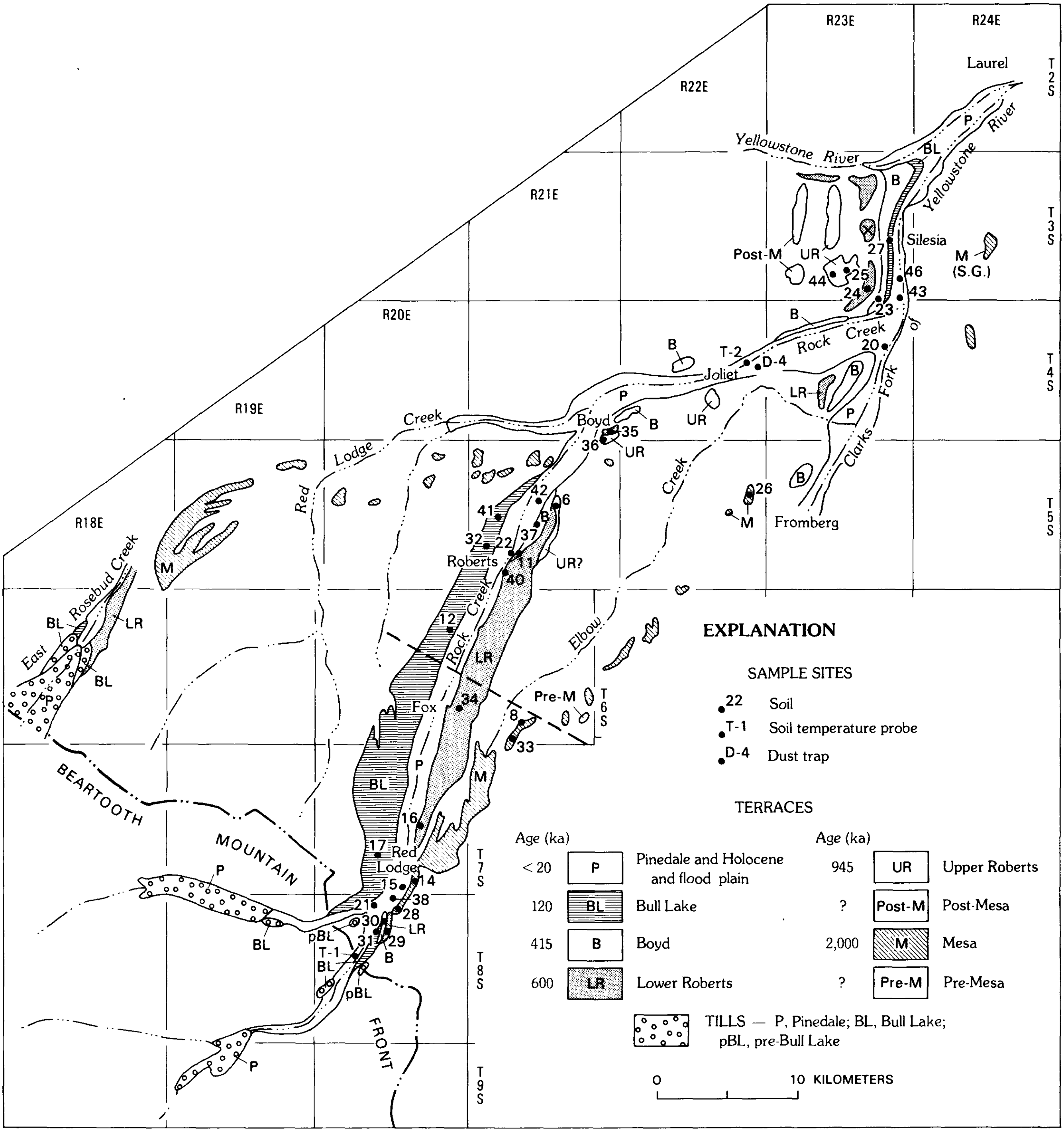


Figure 2. Terraces and tills near Rock Creek, East Rosebud Creek, and Clarks Fork (modified from Ritter, 1967). Mapping for this study extends downstream from Joliet and up the Clarks Fork from its confluence with Rock Creek. The X in T. 3 S., R. 23 E. is Lava Creek ash site. Dashed line approximates Nye-Bowler lineament zone in Rock Creek valley (Zeller, 1963). Mesa remnant labeled S.G. in northeast is Ritter's (1975) Silesia gravel. Sample sites are numbered as in text except that the RC- prefix for the soil sites is deleted.

shale and sandstone. The terraces closely parallel the modern course of Rock Creek (fig. 2), with the exception of Mesa terrace, which traces a former more easterly course of the creek (Ritter, 1967).

Terrace gradients along Rock Creek are variable with respect to the modern stream gradient (fig. 3 and table 1). The gradient of the Pinedale terrace closely parallels that of Rock Creek, but gradients of older terraces parallel Rock Creek only above Red Lodge. Between Red Lodge and Fox (fig. 2), the pre-Pinedale terraces have gradients steeper than the creek, and below Fox their gradients are more gentle than that of Rock Creek. Several hypotheses can account for the changes in terrace gradients relative to the gradient of Rock Creek.

1. The sediment delivered to Rock Creek during pre-Pinedale glaciations could have exceeded the Pinedale sediment load. The creek would have aggraded in order to transport the increased load, forming a wedge of gravel with a steeper upper surface than that of Pinedale age. This hypothesis can only account for terrace gradients upstream from Fox.

2. Local base level for Rock Creek is the Clarks Fork, which may incise more rapidly because of its greater discharge and drainage area. Rock Creek may incise more rapidly downstream than near the mountain front as it keeps pace with the Clarks Fork, and terraces deposited by the creek would therefore diverge away from the modern flood plain. This hypothesis may account in part for the decreased gradients of pre-Pinedale terraces downstream from Roberts. However, the gravel load of either stream, rather than discharge or nature of the stream bed, may be the most important control on downcutting.

3. The nature of the underlying bedrock could affect the gradient of Rock Creek relative to its terraces. However, because bedrock is uniform (Zeller, 1963; Wanek, 1963) through the gradient "hinge" area near Fox, this hypothesis is rejected.

4. Pre-Pinedale tectonic movements near the Beartooth front could have affected the gradients of older terraces (Reheis, 1985). The Nye-Bowler lineament is a major structural feature, active at least up to Eocene time, that crosses Rock Creek valley (figs. 2 and 3) 2 km north of Fox (Wilson, 1936; Zeller, 1963). Regional tectonic forces could cause local Quaternary deformation. Rapid erosion and removal of sediment from the Bighorn Basin relative to the surrounding mountains during late Cenozoic time (Mackin, 1937) theoretically could cause significant rebound of the basin floor (McKenna and Love, 1972). It is intuitively reasonable that rebound would be concentrated along pre-existing zones of weakness, such as the Nye-Bowler lineament.

Some considerations support modification of terrace gradients by late Pliocene or Quaternary movement on the Nye-Bowler lineament: (1) The gradient "hinge" area lies at the intersection of the lineament with the terraces. (2) The change in pre-Pinedale terrace gradients downstream and upstream

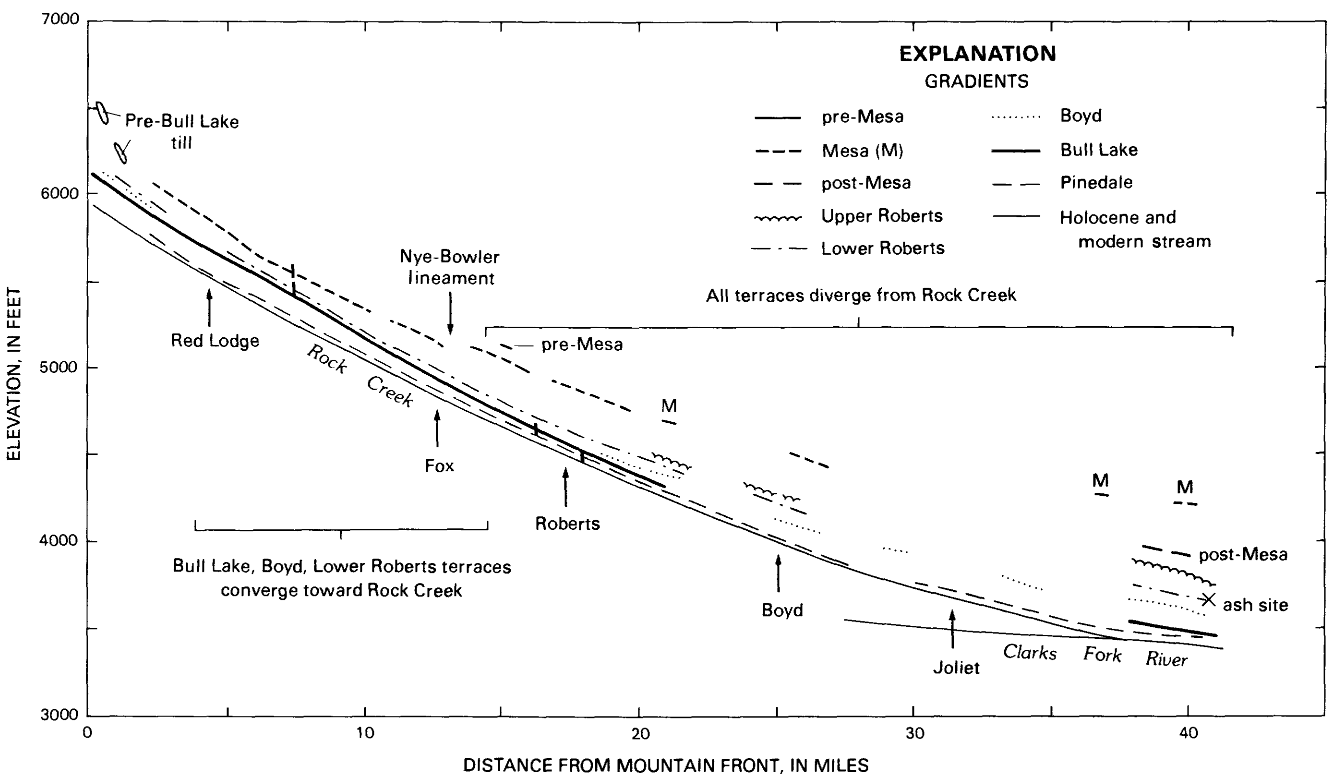


Figure 3. Terrace and river gradients on Rock Creek, beginning at Beartooth front. Small vertical lines on some terraces indicate calcic-noncalcic soil boundary. Mesa gradients projected on a line different from that of modern Rock Creek because they diverge from the creek. X marks position of 610-ka Lava Creek ash.

Table 1. Gradients of Rock Creek and its terraces

Stream or terrace	Red Lodge to Fox		Fox to Clarks Fork	
	ft/mile	m/km	ft/mile	m/km
Modern stream	80	15.1	57	10.8
Pinedale	79	15.0	55	10.4
Bull Lake	88	16.7	55	10.4
Boyd	86	16.3	46	8.7
Lower Roberts	87	16.5	48	9.1
Upper Roberts	not preserved		37	7.0
Mesa	82	15.1	38	7.2

of the lineament is appropriate for the dominantly down-to-the-south movement on the lineament that is documented for the Laramide orogeny (Wilson, 1936). Uplift of the northern block would cause older terraces downstream to diverge from the modern stream gradient more than younger terraces (fig. 3 and table 1). (3) Irregularities in the gradient of the Mesa terrace in the area of the Nye-Bowler lineament suggest that the terrace has been faulted (Reheis, 1985).

The difference between pre-Pinedale terrace gradients and the gradient of Rock Creek probably resulted from tectonic movement caused by isostatic rebound focused on the Nye-Bowler lineament. However, it is possible that increased sediment load from glacial termini near the upper ends of terraces, combined with more rapid downcutting near the Clarks Fork confluence, could underlie the change in terrace gradients.

Climatic Setting

Modern climate and vegetation

Climate is an important factor that governs the rate and style of soil development. Weather data from several towns along Rock Creek and the Clarks Fork, and soil temperature probes at two sites, show that modern climate changes along the stream's course (table 2 and fig. 2). Mean annual precipitation decreases from 64 to 37 cm downstream from mountain to basin, probably due to an orographic effect of decreasing altitude. The largest drop in precipitation occurs within 20 km of the mountain front, and this may be a rain-shadow effect. Mean annual temperature increases from 5.6 to 8.0 °C downstream, but the temperature change is variable, and actually decreases slightly from Joliet to Laurel.

The soil moisture regime (for definitions, see Soil Survey Staff, 1975) changes from borderline ustic-udic (occasionally dry to moist) at the mountain front to aridic (summer dry) in the basin. The soil temperature regime, as indicated by soil temperature probes (Trembour and others, in press), is mesic (8 °C or higher mean annual soil temperature) along the entire length of the transect, although this regime borders on cryic (below 8 °C) at Red Lodge. Estimates of soil temperature from mean annual temperature, which do not account for local factors such as snow depth (Soil Survey Staff, 1975), also suggest a mesic regime except at Red Lodge, where estimated soil temperature is 1.4 °C below the lower limit permissible for a mesic regime.

Table 2. Climatic data summary and full-glacial climate reconstruction for towns along Rock Creek and the Clarks Fork of the Yellowstone River, Mont.

[Derivation of estimated glacial temperatures is discussed in text. All data from National Climatic Center (1951-1980) and the town of Red Lodge. Records from Red Lodge span 77 years; Joliet has a 24-yr record; Roberts and Laurel rainfall records are for 30 yrs. Temperature data shown for Laurel are from a 75-yr record at nearby Billings. Mean annual soil temperature from probes (T-1, Red Lodge; T-2, Joliet) is for 1981-82. Towns are arranged in downstream order from left to right (see fig. 2)]

	Red Lodge		Roberts	Joliet		Laurel	
	now	glacial	now	now	glacial	now	glacial
Altitude (m)	1757		1397	1141		1006	
Mean annual air temperature (°C)	5.6	-4.4	—	8.3	-1.7	8.0	-2.0
Mean July air temp. (°C)	17.9	4.9	—	20.7	7.7	21.9	8.9
Mean January air temp. (°C)	-5.4	-10.4	—	-6.2	-11.2	-4.9	-9.9
Mean annual soil temp. from probes (°C)							
at 0.5 m	8.7	-1.3	—	10.3	0.3	—	—
at 1.0 m	8.7	-1.3	—	9.5	-0.5	—	—
Mean annual soil temp. estimated from air (°C)	6.6	-3.4	—	9.3	-0.7	9.0	-1.0
Mean annual precipitation (cm)	64	64	39	40	40	37	37
Leaching index (cm)	26	44	—	10	22	8	24

Climate may vary locally among the individual soil sampling sites (fig. 2). The site-specific climate may be affected by height above the present drainage and by proximity to higher topography. These factors can alter temperature and wind patterns to cause local accumulations or depletions of snow. The mountain-front and basin soils were sampled in close proximity in each area, so modern climate is considered constant within these chronosequences. In contrast, the transition soils were sampled at various distances from the mountain front, because the calcic-noncalcic soil boundary varies with terrace age. As a result, soils of the transition chronosequence are in a more varied modern climate than are the mountain-front or basin soils.

The soil sample sites are presently vegetated by grass (supplementary table 1), although the types of grasses change along the elevation transect. The Holocene and post-Pinedale soil sites at the mountain front have tall grasses and forbs with aspen or conifer trees nearby. Higher terraces in this chronosequence are covered with tall grasses, forbs, and some sagebrush. As the climate becomes drier downstream, tall grasses give way to shorter grasses and bunch grass, some mineral soil is exposed, the proportion of sagebrush increases, and cactus is common where pasture has been overgrazed. During glaciations, vegetation cover probably became more dense in the basin. Terraces close to the mountain front may have been forested, but only the post-Bull Lake soil RC-31 (Rock Creek-31) (soil site 31 on fig. 2) shows any indication of former forest cover.

Some soils were sampled in or at the edge of cultivated fields (supplementary table 1). Unplowed soils are particularly difficult to find anywhere on the Bull Lake terrace below Red Lodge, or on the Pinedale terrace in the basin.

Evidence documenting paleoclimate

Characterizing the modern climate adequately describes the climate of the Holocene, but fails to describe the climate during glacial periods. More moist glacial periods probably had important effects on soil development near Rock Creek, so it is important to discuss the available evidence concerning paleoclimate.

Mears (1981) estimated a mean annual decrease in temperature of 10-13 ^{o}C for the intermontane basins of Wyoming during the last glaciation, based on preservation of ice- and sand-wedge polygons in Quaternary deposits. This estimate of cooler temperature is compatible with glacial-to-present snowline changes if the effect of altitudinal gradients of precipitation is considered (Pierce, 1982). A pollen sequence in Yellowstone Park shows that the upper treeline was depressed by about 500 m before 11.6 ka (Waddington and Wright, 1974).

From modeling the global climate at 18 ka, Gates (1976) suggested a July temperature decrease of 13 ^{o}C for the Yellowstone-Bighorn region and a 30 percent decrease in precipitable moisture in the northern hemisphere. A precipitation decrease is reasonable because the presence of a large stable high-pressure zone over the continental ice sheets north of the study area would have caused year-round dominance of dry northerly air flow, whereas the present southerly air flow in spring and summer delivers moisture from the Gulf of Mexico. Galloway (1983) pointed out that moisture derived from the Gulf of Mexico may have been sharply reduced during glaciations, because low sea levels greatly reduced the water-surface area. However, no geologic or palynologic evidence has been found in the study area to date which supports such a moisture decrease.

Vertical clast orientations (common in frozen ground) in a Lower Roberts terrace deposit (ash site, fig. 2; ctr. NE1/4NE1/4 sec. 22, T. 3 S., R. 23 E., Silesia, Mont., 7 1/2-minute quadrangle) suggest that the climate just prior to 610 ka may have been similar to that of the last glaciation. Deposits of 610-ka Lava Creek A and B ashes (identified by R. Wilcox, oral commun., 1983), in places thinned or cut out by overlying colluvium, cap 2 m of well-sorted cross-bedded fluvial sand and granules (fig. 4A). These sands overlie a very weak paleosol, similar in its development to the modern soil on Holocene-aged deposits, that has formed in fluvial sandy gravel. The paleosol has 4 percent more $CaCO_3$ than the overlying sand and 3 percent more clay than the underlying gravel. Clasts in and just below this buried soil are preferentially oriented with long axes vertical (fig. 4B). Clasts above and below this zone are oriented horizontally or are imbricated, as is normal for fluvially deposited gravels. These deeply buried clasts (4 m deep) must have been vertically oriented during or just before soil formation and before the overlying sand and ash was deposited.

Several studies have found strongly vertical orientations of tabular stones in regions of frost heaving, but not necessarily where modern permafrost is present (Washburn, 1980). Other studies have shown that vertical stone orientations are associated with such permafrost features as patterned ground (Goldthwait, 1976) and ice and soil wedges (Black, 1976). Schafer (1949) reported vertical stones in periglacial involutions of gravel and soil horizons in central Montana. Vertical stone orientations at the ash site in this study probably represent permafrost conditions or intense frost heaving before 610 ka.

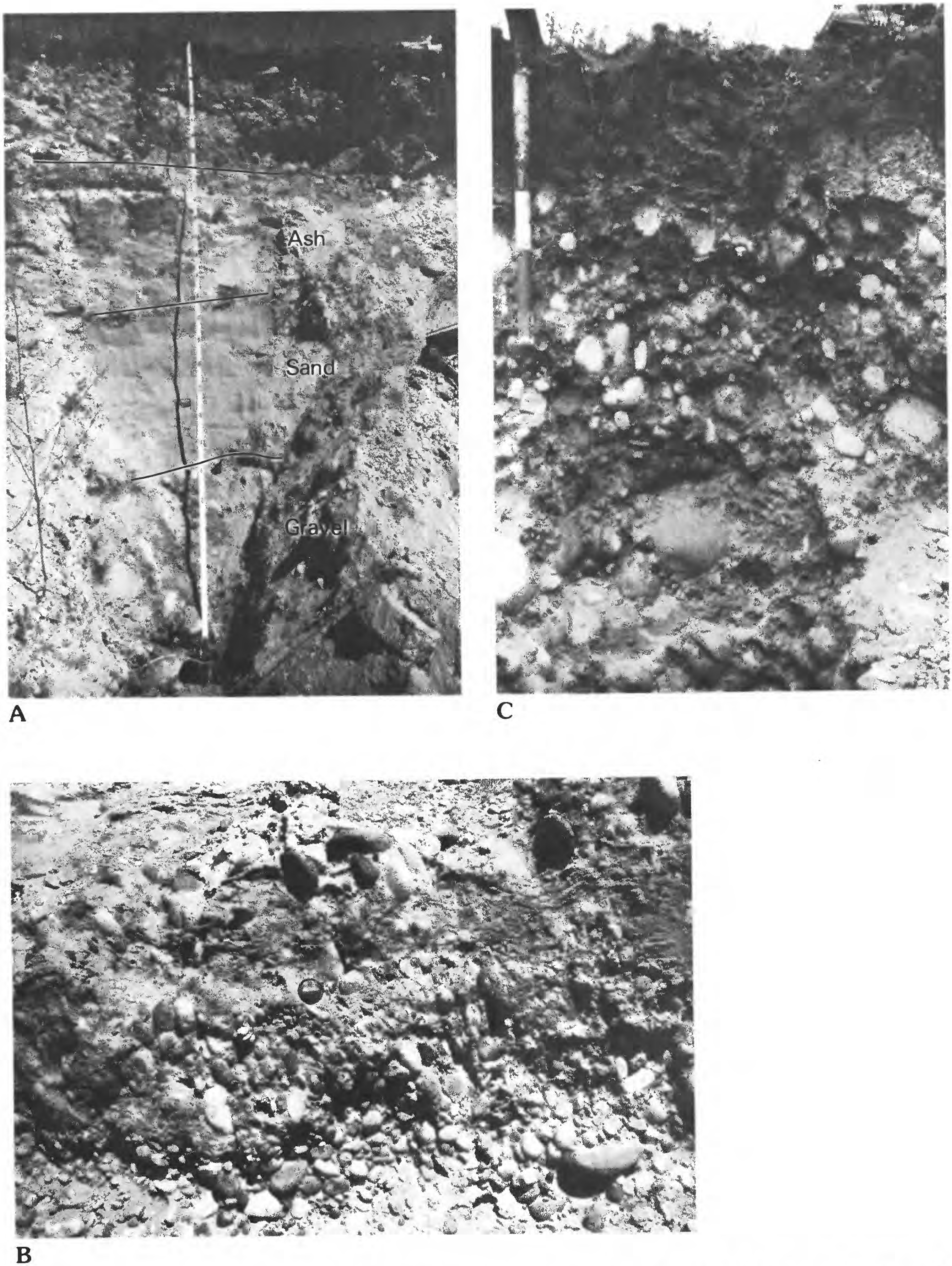
Similar stone orientation occurs in a soil developed on Pinedale terrace deposits (fig. 4C; NE1/4NE1/4NW1/4 sec. 16, T. 5 S., R. 21 E., Cooney Reservoir, Mont., 7 1/2-minute quadrangle), and possible ice wedges were seen by D.F. Ritter (oral commun., 1980) in a gravel pit on the Boyd terrace (SW1/4SW1/4NE1/4 sec. 30, T. 45 N., R. 22 E., Boyd, Mont., 7 1/2-minute quadrangle). These observations suggest the local presence of permafrost during the last glaciation.

Paleoclimatic reconstruction

I reconstruct glacial climate in more detail by calculating hypothetical monthly variations in temperature and evapotranspiration along Rock Creek (table 2), assuming that (1) mean annual temperature was 10 ^{o}C lower than present, (2) mean July temperature was 13 ^{o}C lower, and (3) mean January temperature was 5 ^{o}C lower. No evidence is available concerning glacial winter temperature, but some lowering probably occurred. Temperatures for other months are adjusted to fit the constraints on mean annual, July, and January temperatures. Glacial precipitation is held at modern levels in order to test the decrease in precipitation suggested by Gates' (1976) model. Evapotranspiration is calculated from monthly temperature data using van Hylckama's method (1959). Diagrams of soil temperature and moisture balance compare glacial with modern conditions (fig. 5).

The reconstruction suggests that great changes occurred in climatic regime and soil conditions in glacial periods. Soils dry out during the summer under the modern ustic and mesic (or cryic) soil climate at Red Lodge; in glacial times, the soils would have been always moist under a udic, pergelic (permafrost) regime. The amount of leaching and percolating water (leaching index of Arkley, 1963) would have more than doubled. If permafrost was present, however, surplus water may have been held in the active layer or may have drained away laterally rather than vertically. The glacial climate of the present dry ustic, mesic area of Joliet would have been similar to that of present-day Red Lodge, but colder. The climate at

Figure 4. Lava Creek ash site and vertical stone orientations in terrace gravels. A, Stratigraphy at ash site (fig. 2). Divisions on tape are 10 cm. Haft of knife at center of photograph is at lower boundary of ashy sand, capped 50 cm higher by thin-bedded ash and pumice. Thin buried soil begins at top of gravel, lower one-third of photo. B, Vertical stone orientations in buried soil of ash site; lens cap is 5 cm in diameter. C, Vertical stones in Pinedale terrace north of Roberts; white band on pick is 10 cm long. Exact site locations given in text.


Ash
Sand
Gravel
A
C
B

Laurel, now aridic and mesic, would have been ustic and pergelic. In glacial times, surpluses of water would have been available in the spring for leaching at Joliet and Laurel, whereas at present no surplus exists in most years. These postulated changes have important connotations for soil development, particularly with respect to precipitation or solution of pedogenic $CaCO_3$.

GEOLOGIC SETTING AND CHRONOLOGY

Previous Work

The regional relations among terrace deposits of the rivers in the northern Bighorn Basin have been studied since the early 1900's. Alden (1932) published maps and descriptions of terraces in eastern Montana, including those along Rock Creek, and he believed that the oldest terraces were Tertiary in age. Mackin (1937) extended these studies southward in his classic work on the erosional history of the Bighorn Basin, as did Andrews and others (1947).

Glacial deposits in the Beartooth Mountains (Bevan, 1946) have been studied in Yellowstone National Park (summarized in Pierce, 1979), the headwaters of the Clarks Fork of the Yellowstone River (Pierce, 1965; Ballard, 1976), on the Stillwater River northwest of Rock Creek (Ten Brink, 1968, 1972), and on Rock Creek (Ritter, 1967; Graf, 1971).

Ritter (1967, 1972, 1974) discussed the genesis of terrace gravels on Rock Creek, identified deposits correlative to the Pinedale and Bull Lake glaciations, and reconstructed the regional drainage pattern during Mesa time. Ritter's work provides the basic terrace stratigraphy, but I amplify his stratigraphy and extend his mapping downstream to the Yellowstone River.

The bedrock and structural geology in and along the Beartooth Mountains has been described by Foose and others (1961), Wanek (1963), Zeller (1963), Pierce (1965), and Patterson (1966).

Source of Deposits

Bedrock in the glaciated headwaters of Rock Creek (fig. 2) is composed mainly of granitic gneiss with some amphibolite and mafic intrusive rocks (Foose and others, 1961). The Paleozoic and Mesozoic section, 3,300 m thick, is exposed along the Beartooth front in faulted, steeply dipping beds dominated by Paleozoic carbonate rocks. Tertiary nonmarine clastic rocks fringe the mountains (Ritter, 1967; Pierce, 1978). Downstream from Roberts, exposed bedrock consists mainly of Cretaceous shale and sandstone that is somewhat more resistant than the Tertiary sediments. Tertiary sediments are preserved away from the valley walls north of Roberts, but have been removed by erosion between Joliet and Laurel (Wanek, 1963; Patterson, 1966). Though various sedimentary rocks crop out along the course of Rock Creek, the terrace gravels are composed almost exclusively of the igneous and metamorphic rocks of the Beartooth Mountains. Carbonate rocks compose less than half a percent of the deposits, and less resistant rock types are not recognized.

Along the Clarks Fork, the terrace deposits contain andesitic debris derived from the volcanic rocks of the Absaroka Range. Above the mouth of Rock Creek, the terrace deposits contain from 35 to 65 percent andesitic gravel (Mackin, 1937; Ritter, 1975); below the mouth of Rock Creek, deposits on the west side of the river contain about 10 to 20 percent andesitic gravel because of dilution by the granitic debris contributed by Rock Creek.

Parent Material—Nature and Variability

The parent material is another important factor in soil development. If the parent materials of the soils on Rock Creek terraces are different, then differences in the soils cannot be ascribed to either time or climate. Thus, it is critical to compare stable physical and chemical properties of the alluvial deposits.

The parent material for most of the sampled soils is compositionally similar, consisting of granitic gneiss with some amphibolite and mafic intrusive rocks (visual estimate). The basin soils, except those on the Mesa terrace, have about 15 percent andesitic detritus contributed by the Clarks Fork. This proportion is slightly higher in soil RC-27, because it was sampled downstream from the confluence of Rock Creek with the Clarks Fork (fig. 2).

Gravel percentage decreases and fines increase upward in each soil profile, which is due in part to upward fining in the fluvial parent material. Three soils do not fine upward: RC-27, the post-Bull Lake basin soil; and RC-25 and RC-36, the post-Upper Roberts basin and transition soils. Soil RC-27 (supplementary table 1) has nongravelly, finely bedded calcareous sandy silt interlayered with sandy gravel. This soil is located on a narrow terrace near a small drainage that is presently depositing an alluvial fan below the terrace. Apparently the small drainage was also active during Bull Lake time and contributed the layer of sandy silt found in the soil. The two anomalous post-Upper Roberts soils (supplementary table 1) occur on deposits with gravelly alluvium at the surface, overlying massive, finer calcareous materials that contain a few clasts floating in the fine matrix. The shallow hole at sample site RC-25 did not penetrate these finer materials. The excavation at sample site RC-36 penetrated 1.2 m of very clayey, silty calcareous sediments, then met the usual sandy gravel. The fine materials resemble deposits made by debris flows.

Chemical uniformity of the parent material both within and among soil profiles was examined using titanium-oxide to zirconium-oxide ratios of the silt-plus-clay fraction (TiO_2/ZrO_2; data in supplementary table 5). Titanium and zirconium are primarily contained within the minerals rutile and zircon, which are very resistant to weathering (zircon is most resistant). Generally, the proportion of TiO_2 to ZrO_2 should reflect the composition of the parent material. Thus, abrupt changes in the TiO_2/ZrO_2 ratio with depth probably reflect changes in the parent material chemistry rather than changes due to weathering (Chapman and Horn, 1968; Smeck and Wilding, 1980).

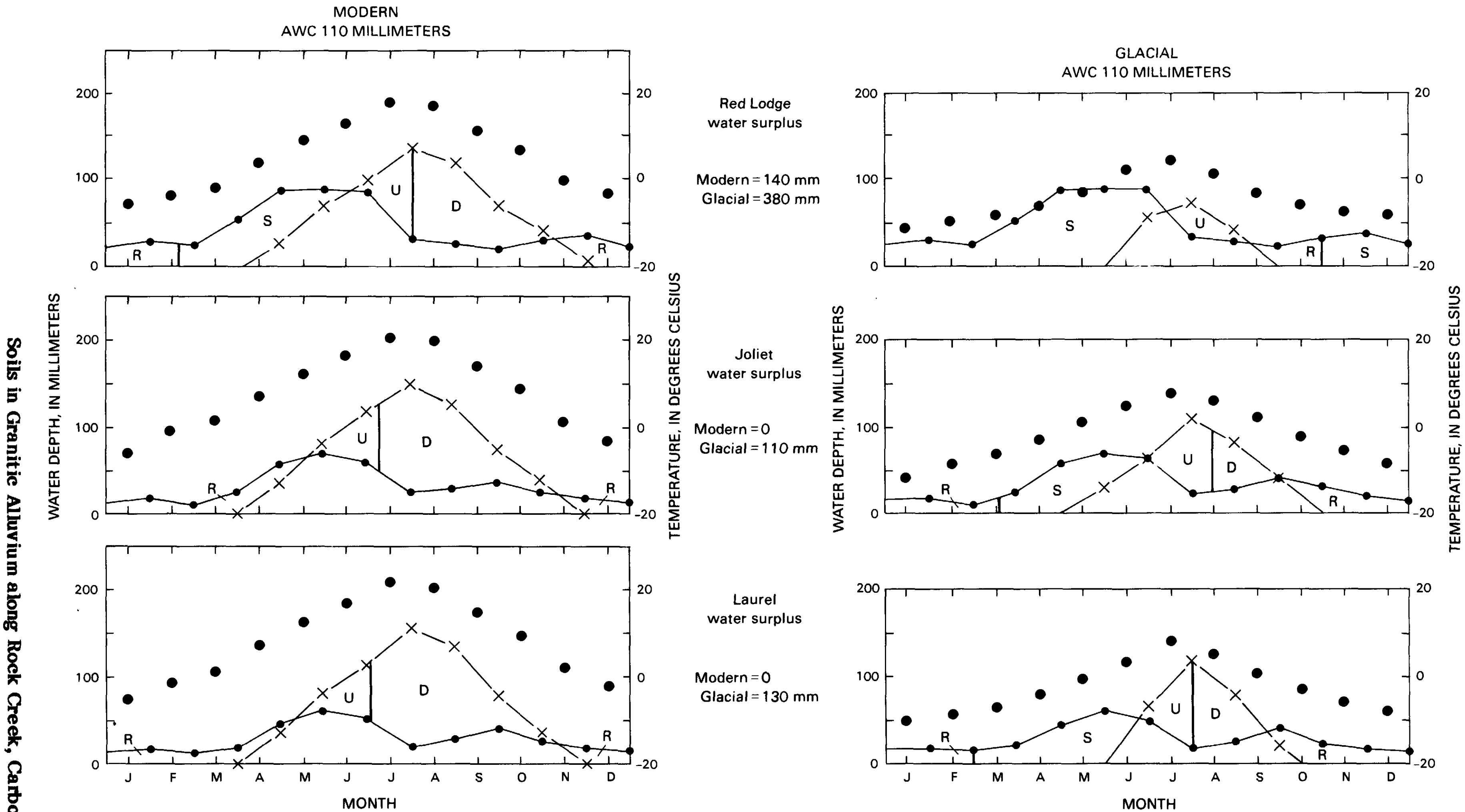


Figure 5. Modern (left column) and last-glacial (right column) climate and soil-water balances for Red Lodge, Joliet, and Laurel (lengths of record in table 2). Reconstruction of glacial temperatures described in text. Large dots are air temperatures (in degrees Celsius), small dots are precipitation (in millimeters of water), and X's are inferred values for evapotranspiration (in millimeters of water). Soil AWC (available water-holding capacity) of 110 mm is average for Rock Creek soils; young soil AWC's are usually less than 110 mm, older soil AWC's are usually more than 110 mm. R, period of recharge of soil water up to 110 mm when precipitation exceeds evapotranspiration; S, period of surplus water after soil is charged; U, period of utilization of stored soil water when soil is dry in some part, because evapotranspiration exceeds precipitation; D, deficit period when soil moisture control section is dry.

TiO_2/ZrO_2 ratios for the population of all horizons (13 soil profiles, plus additional horizons from other profiles) have a mean ($\bar{x}$) of 14.5 and a standard deviation (s) of 4.3 (table 3). Only 3 horizons out of 86 exceed 2s from the mean for all horizons. Many of those that exceed 1s are B horizons in which titanium-bearing minerals may be weathering (Chapman and Horn, 1968; Wilding and others, 1971). Relative variability among different groups was examined by the coefficient of variability ($s/\bar{x}$); for all horizons $s/\bar{x}$ is 30 percent, whereas that for C horizons is 52 percent. Part of the variability is due to changes in deposition along Rock Creek, because within-profile variability (comparing the horizons of one soil profile) is quite low: the mean of within-profile variability for Ti/Zr ratios is 16 percent. Because ratios for all but three horizons fall within 2s of the mean ratio, the variation is considered normal for the population, suggesting that the parent materials are chemically similar.

Textural variability is estimated by calculating coarse to very coarse sand (C/VC) ratios and medium to coarse plus very coarse sand (M/C+VC) ratios for all horizons of all profiles (supplementary table 2), assuming that losses by solution from coarse grains are not significant (Harden, 1982a). Large sand grains in Rock Creek deposits are commonly polycrystalline and may rapidly break down into smaller fragments; however, grusification of granitic gravel replenishes the coarser sand fractions, so gains and losses in these fractions may cancel out.

C horizon textures among all soils on Rock Creek are variable ($s/\bar{x}$ for C/VC = 86 percent, $s/\bar{x}$ for M/C+VC = 88 percent; table 3), but within-profile variability for all horizons is less (mean of C/VC = 39 percent, M/C+VC = 35 percent). Harden (1982a) also found that within-profile variability was less than half that of between-profile variability in Merced River soils of California. This suggests that deposition changes more from place to place than it does vertically at one place. Among all 33 profiles of Rock Creek, 6 profiles each had one C horizon that was significantly different in both sand ratios from the other horizons in the profile, and these probably represent initial depositional layering. For comparison, the textural variability of Rock Creek soils is less than that in Merced River soils (Harden, 1982b), where within-profile variability averages 44 percent for both C/VC and M/C+VC ratios, and between-profile variability is 114 percent for M/C+VC and 96 percent for C/VC ratios.

In summary, the fluvial parent materials are lithologically and chemically similar but vary in grain size. Textural variability is greater than chemical variability due to the nature of fluvial processes, assuming that different size fractions have similar chemical compositions. No data are presently available to check this assumption. Hence, differences among the soils developed on the Rock Creek terraces primarily reflect differences in age and in climate.

Table 3. Parent material variability within and among soils of Rock Creek

[N is number of cases, $\bar{x}$ is mean, s is standard deviation, $s/\bar{x}$ is percent variability]

Variability	N	$\bar{x}$	s	$s/\bar{x}$
Among profiles:				
Ti/Zr, all horizons	86	14.5	4.3	30
Ti/Zr, C horizons	16	13.8	7.2	52
C/VC, C horizons	69	2.0	1.7	86
M/C+VC, C horizons	69	0.6	0.5	88
Within profiles:				
mean of s/x for Ti/Zr	13	--	--	16±7 (1s)
mean of s/x for C/VC	33	--	--	39-28 (1s)
mean of s/x for M/C+VC	33	—	--	35±19 (1s)

Stratigraphic Units and Origin

Seven major terraces deposited by Rock Creek and the Clarks Fork extend downstream from the mountain front to the Yellowstone River (fig. 2). Informal terrace names are modified from Ritter (1967). His terminology has been expanded as follows: (1) A Holocene terrace was mapped. (2) The Roberts terrace was divided into upper and lower units. Near the downstream limit of Ritter's mapping at Joliet, the Roberts terrace remnants diverge into two terrace levels. The Lower Roberts terrace of this paper is equivalent to Ritter's Roberts terrace. (3) Eroded remnants of an eighth terrace, called the post-Mesa terrace, were mapped in the angle of land formed by the Yellowstone River, the Clarks Fork, and Rock Creek. It is intermediate in age between the Upper Roberts and Mesa terraces. (4) A single small remnant of gravel (called pre-Mesa) stands higher than the Mesa terrace about 15 km northeast of Red Lodge. The pre-Mesa and post-Mesa terrace remnants were not sampled in this study due to poor preservation.

Both stream capture and glaciofluvial deposition have been proposed as methods of terrace formation along Rock Creek. The mode of terrace formation is important, for if the terraces are glaciofluvial, then they are related to regional climatic fluctuations that can provide a chronologic framework for those terraces not directly dated.

Mackin (1937) and Ritter (1967, 1972) proposed that terrace formation by stream capture in the Bighorn Basin is frequent because mountain-bred streams are forced to maintain steep gradients to carry coarse detritus, whereas basin-bred tributaries can transport their fine sediment load with lesser flow and lower gradients. Thus, a headward-eroding basin tributary flows at a lower level than an adjacent main stream and easily captures the mountain stream. The flood of gravel introduced into a relatively small drainage causes the stream to aggrade, forming a fill terrace, until it reaches a gradient steep enough to transport the new gravel.

Ritter (1967) also suggested, in contrast to the hypothesis of terrace formation by stream capture, that the gravel underlying at least two and probably all of the terraces along Rock Creek has a glaciofluvial origin. He did not attempt to reconcile the apparent contradiction between the climate-induced deposition of the terrace gravel and the capture-induced formation of the terrace surface.

The relationship between terrace formation by capture and glaciofluvial gravel deposition might be explained as follows. A mountain-bred stream begins to receive glacial debris and increased water flow during a glaciation. A tributary stream in the basin also receives increased moisture but no glacial debris, so it can begin or accelerate downcutting and headward erosion, either outside or along the valley wall of the main stream (Ritter, 1967). The tributary stream captures the glacial stream and immediately aggrades, depositing a fill terrace of glaciofluvial gravels. When glaciation ends, the amount of water and the debris load are reduced. Once the river equilibrates to these conditions, it cuts down slowly, and abandons its former flood plain. Thus, a terrace surface underlain by glaciofluvial gravel can be formed by capture during a glaciation.

The terrace deposits along Rock Creek and the Clarks Fork are probably glaciofluvial in origin, except for those of Holocene age. The Pinedale terrace can be traced up Rock Creek directly into Pinedale-aged moraines (Ritter, 1967), west and southwest of Red Lodge (fig. 2), and a reasonable case can be made for associating the next higher terrace with less well preserved moraines southwest of Red Lodge, considered to be Bull Lake in age. The equivalent terrace in the valley of East Rosebud Creek north of the study area can be traced directly into Bull Lake lateral moraines (fig. 2; discussed in Ritter, 1967). The glaciofluvial nature of terrace deposits older than Bull Lake is inferred from other evidence and from the resemblance of these deposits to known glaciofluvial deposits.

Ritter (1967) suggested that remnants of pre-Bull Lake till near Red Lodge and in the valleys of East and West Rosebud Creeks were at the proper height and position to be genetically related to the Boyd terrace gravels. Careful reconstruction of terrace gradients (fig. 3) suggests that the Lower Roberts or some older terrace is more closely related to the old tills east and west of Rock Creek at the Beartooth front (fig. 2). The tills are poorly preserved, have thin soils, and consist mainly of boulders draped over bedrock ridges. The tills have probably been lowered by erosion and it is likely that they correspond to a terrace older than the Boyd.

Stratigraphic relations at the Lava Creek ash locality (figs. 2 and 4) suggest that the Lower Roberts terrace gravel was deposited during or just before an interval of cold climate. Corroboration of the glaciofluvial nature of the Lower Roberts deposits is found in East Rosebud Creek (fig. 2), where a pre-Bull Lake till is buried beneath the eastern Bull Lake lateral moraine (roadcut, NE1/4NW1/4NE1/4 sec. 16, T. 6 S., R. 18 E., Mackay Ranch, Mont., 7 1/2-minute quadrangle). At the terminus of this moraine, till of Bull Lake age appears to lie on a terrace that is equivalent to the Lower Roberts terrace in Rock Creek valley (Ritter, 1967). The projected gradient on this terrace intersects the buried pre-Bull Lake till.

The glaciofluvial nature of the Boyd, Upper Roberts, and Mesa terrace deposits is indicated by their resemblance to glaciofluvial deposits in thickness and boulder size (Ritter, 1967). More than one pre-Bull Lake glaciation occurred in other areas of the Rocky Mountains (Richmond, 1976), and it is possible that the several pre-Bull Lake till remnants on the Beartooth front represent different glaciations. The Mesa terrace may be indirectly linked to a late Pliocene glacial episode in Jackson Hole, Wyo. There, till of pre-Bull age is overlain by pumicite of the 2-m.y.-old Huckleberry Ridge eruption in Yellowstone (Love, 1976, and oral commun., 1983). Ash of the same eruption overlies terrace gravels that are correlated with Mesa deposits to the east of Rock Creek.

Geochronology

Chronologic control on the abandonment of the terrace surfaces is necessary to estimate rates of soil development. Several dating methods were employed in this study, including correlation with dated deposits in West Yellowstone, Mont., tephrochronology of two ash sites, calculation of incision rates, and comparison to the marine oxygen-isotope record. The ages of the Pinedale, Bull Lake, Lower Roberts, and Mesa terraces are discussed first because these ages are most closely constrained. From these ages, incision rates are calculated in order to estimate the ages of the Holocene, Boyd, and Upper Roberts terraces.

Soil formation commences on fluvial deposits when the depositing river begins to incise. The Rock Creek terraces are composed of glaciofluvial gravel deposited at progressively lower altitudes during successive montane glaciations. It follows that the minimum time since the commencement of soil formation on a terrace is the time at which the succeeding interglaciation ends. By that time, the river must have cut down to a lower level at which it will deposit the next younger outwash. By analogy to the Pinedale glaciation, however, the most likely time for commencement of soil formation on a particular terrace is close to the end of the glacial advance that deposits the terrace gravel, rather than at the end of the following interglacial (discussed below).

Age of the Pinedale terrace

Ritter (1967) correlated the lowest major terrace deposit of Rock Creek (not counting the Holocene deposits) and its associated moraines with the Pinedale glacial advance based on moraine morphology; the moraines are sharp-crested, bouldery, and have many undrained depressions. Pierce and others (1976) used obsidian hydration rates to obtain an age of 30 ka for the Pinedale terminal moraine in West Yellowstone, with younger recessional deposits dating between 10 and 15 ka.

The Pinedale terrace along Rock Creek stands 8 to 15 m above the modern stream (table 4). This incision must have occurred some time ago, given the profile depth, color, and clay content of the soils on the Pinedale terrace. Moreover, younger Holocene fill terraces now 3 to 5 m above Rock Creek have been formed and incised since the Pinedale terrace was

Table 4. Stratigraphic units and ages of the Rock Creek soil chronosequence

[Height column gives mean and standard deviation (N = 4-8) of height of terrace above Rock Creek north of Roberts and above the Clarks Fork at Silesia (used in fig. 8)]

Named terrace deposits	Age control (ka)	Best estimate and range for surface age (ka)	Height (m)		Comments
			Roberts	Silesia	
Holocene	0 2[1] 10[2]	7 (2-10) [7]	3.3±0.9	5.4±1.5	Post-last glaciation
Pinedale	10[2] 30[2]	20 (10-30)	7.8±1.6	15.0±3.0	Correlated with dated West Yellowstone Pinedale deposits
Bull Lake	75[3] 90[1] 150[2] 200[1]	120 (90-150)	17.5±2.1	30.2±1.9	Correlated with dated West Yellowstone Bull Lake deposits
Boyd	295[1] 347[4] 410[4] 440[4] 515[1]	415 (295-515) [7]	28.5±5.6	64.7±7.6	Younger than Lower Roberts terrace, older than Bull Lake terrace; age of Boyd at mountain front uncertain
Lower Roberts	542[3] 610[5]	600 (541-610)	47.8±4.5	88.1±4.4	Lava Creek A and B ashes mark end of fluvial deposition
Upper Roberts	770[1] 870[4] 950[4] 1095[1]	945 (770-950) [7]	64.6±4.8	128.9±8.0	Younger than Mesa terrace, older than Lower Roberts terrace
Mesa	1950[3] 2010[6]	2000 (1950-2010)	125.3±5.1	252.3±10.5	Huckleberry Ridge ash marks end of fluvial deposition

[1]Minimum or maximum age derived from estimated incision rate of Clarks Fork (fig. 7 and text discussion).
[2]Date from obsidian hydration on Pinedale deglacial deposits, Pinedale terminal moraine, and Bull Lake moraines, West Yellowstone (Pierce and others, 1976).
[3]End of interglacial stages (presumed minimum terrace dates) as determined from marine oxygen-isotope curves: stage 5 (Bull Lake) and stage 15 (Lower Roberts) of Shackleton and Opdyke (1976); stage 41 (Mesa) of van Donk (1976).
[4]End of glacial stages (presumed most likely terrace dates) as determined from marine oxygen-isotope curves: for Boyd terrace, stages 10, 14, and 12, respectively; for Upper Roberts terrace, stages 24 and 26, respectively. Stages 10 and 12 from Shackleton and Opdyke (1976); stages 14, 24, and 26 from van Donk (1976).
[5]Lava Creek A and B ashes erupted from Yellowstone Park area (Izett, 1981).
[6]Huckleberry Ridge ash erupted from Yellowstone Park area (Izett, 1981).
[7]These best-estimate ages are derived from incision-rate calculations as described in text; 5-ka accuracy of the ages is not implied.

abandoned. Major deglaciation occurred in the Rocky Mountains by 14 ka (Porter and others, 1983). Hence, the Pinedale terrace was probably incised and soil formation commenced within 10 ka after the glacial outwash was deposited. This number will be used in the following discussions to approximate the time of incision of other terraces.

Soils on the Pinedale terrace of Rock Creek were sampled on the highest of several terrace levels,[2] which probably corresponds with the maximum glacial advance. By analogy to West Yellowstone, the highest Pinedale surface was probably abandoned by the river sometime after 30 ka. I assign an age of 20 ka to this surface and the soils on it, but they could be as young as 10 ka or as old as 30 ka (table 4).

Age of the Bull Lake terrace

Ritter (1967) correlated the next higher terrace deposit and moraines with the Bull Lake glaciation. These moraines (fig. 2) have rounded crests, fewer surface boulders than Pinedale moraines, and few undrained depressions. Pierce and others (1976) and Pierce (1979) obtained ages ranging from 130 to 150 ka on obsidian in Bull Lake moraines of West Yellowstone. Whether all Bull Lake moraines in the Rocky Mountains predate the last interglacial is debatable, but the assumption seems reasonable for Rock Creek deposits in part because of their proximity to the dated Yellowstone deposits. Moreover, the assumption can be checked by calculating the age of the Bull Lake terrace from incision rates derived from other terraces (discussed below).

The Bull Lake terrace surface was probably abandoned sometime after 130 ka; thus, this terrace and its soils are assigned an age of 120 ka (table 4). The terrace is probably no older than 150 ka if the correlation with Bull Lake deposits in West Yellowstone is correct. The Bull Lake terrace deposits are glaciofluvial and the terrace probably was stabilized during the following interglacial period. Therefore, the Bull Lake terrace is probably no younger than the end of the interglacial oxygen-isotope stage 5, or about 75 ka (Shackleton and Opdyke, 1976).

Age of the Lower Roberts terrace

The Lower Roberts terrace and soils are dated at about 600 ka (table 4), because the uppermost fluvial deposits in this terrace include lenticular beds of the Lava Creek A and B ashes (ash site, fig. 2; identified by R. Wilcox, oral commun., 1983). The thin buried soil between the ashes and the coarse gravel suggests a short depositional hiatus of perhaps 5,000 years. The intervening sediments and the ash itself are both fluvial deposits, and the ashes can have been reworked little, because discrete beds of the two closely spaced Lava Creek A and B eruptions are preserved. Thus, the ashes must date the end of aggradation at 610 ka (Izett, 1981).

The Lower Roberts terrace surface was abandoned after deposition of the ashes. From the deep-sea oxygen isotope record, interglacial stage 15 follows the Lava Creek eruption and ends at about 542 ka (Shackleton and Opdyke, 1976). The Lower Roberts terrace and soils are probably no younger than this.

Age of the Mesa terrace

The age of the Mesa terrace (table 4) is inferred by a series of correlations with a terrace of the ancient Shoshone River east of Pryor Creek, about 40 km west of the study area (figs. 1 and 6). The uppermost fluvial deposits of the Shoshone terrace above Pryor Creek consist of 2,010-ka Huckleberry Ridge ash (Izett and Wilcox, 1982). This terrace can be traced nearly continuously to a point 295 m above the Yellowstone River, at which point the lithology of the terrace gravel indicates that it was deposited by the Yellowstone and Shoshone Rivers combined (Reheis and Agard, 1984). This terrace is correlated with two groups of Clarks Fork terrace remnants at similar heights above the Clarks Fork (fig. 6). One group is about 10 km east of Billings, and the other group, parts of which were called the Silesia gravel by Ritter (1975), lies east of the Clarks Fork-Rock Creek confluence. Ritter believed that the Silesia gravel is older than the Mesa terrace. However, the Silesia gravel and other nearby gravel deposits lie at the same height above the Clarks Fork and are correlated with

[2]The number of Pinedale terrace levels changes from three or more to one going downstream.

the last Mesa terrace remnant. This Mesa remnant represents the former confluence of the Clarks Fork and Rock Creek, judging from the lithology of sand grains in the terrace deposit.

The age of the Mesa terrace is about 2,000 ka, given the terrace correlation and allowing about 10,000 years for the terrace surface to be abandoned after deposition of the Huckleberry Ridge ash. Oxygen-isotope ratios of a core from the Atlantic Ocean indicate that the end of a warm period following the ash eruption occurred at about 1,950 ka (van Donk, 1976). If the Mesa terrace deposits are glacial outwash, then the terrace was probably abandoned no later than the end of the ensuing interglacial, or about 1,950 ka (table 4).

Ages of remaining terraces from incision rates

Ages for the Pinedale, Lower Roberts, and Mesa terraces are used to suggest tentative ages of the remaining terraces (fig. 7 and table 4). The means and standard deviations of heights above present river level of three dated terraces (Pinedale, Lower Roberts, and Mesa) are plotted against their estimated ages. The dashed lines connecting these points and the origin give average stream-incision rates of 11.7 and 5.5 cm/ka from 2,000 to 600 ka, 12.6 and 6.9 cm/ka from 600 to 20 ka, and 75 and 39 cm/ka from 20 ka to the present, for the Clarks Fork and Rock Creek respectively. The approximate ages of the Holocene, Bull Lake, Boyd, and Upper Roberts terraces are calculated from these incision rates and the means and standard deviations of terrace heights above the river (method of Palmquist, 1979 and 1983). These heights were determined from topographic maps at several places (from four to eight, depending on the number of terrace remnants preserved). The standard deviations of the heights are large because they include errors due to measurement, erosion, and sideslope deposition. The terrace ages are: Holocene, 7 ± 2 ka; Bull Lake, 140 ± 15 ka; Boyd, 415 ± 60 ka; Upper Roberts, 945 ± 70 ka. These are minimum age errors because they only include uncertainties in the undated terrace heights.

The maximum age errors also include uncertainties in the heights and ages of the dated terraces. The error envelope (fig. 7) permits estimation of the maximum errors on the ages of the undated terraces. These errors are: Holocene, 7^{+10}_{-5} ka; Bull Lake, 140^{+50}_{-60} ka; Boyd, 415^{+100}_{-120} ka; Upper Roberts, 945^{+150}_{-175} ka.

Terrace heights were measured in two different areas in order to check the precision of this method: (1) a 20-km reach of the Clarks Fork from Elbow Creek north, and (2) a 15-km reach of Rock Creek from Roberts north (fig. 2). The ages estimated for undated terraces in the two areas are comparable (fig. 7), but the age ranges estimated from the standard deviation of terrace heights are much larger for the Rock Creek reach because the rate of downcutting in that area is half the rate of the Clarks Fork.

The age of the Holocene terrace cannot be evaluated in detail. This terrace consists of a number of levels which could be earliest Holocene to modern in age. However, it is probable that the Holocene

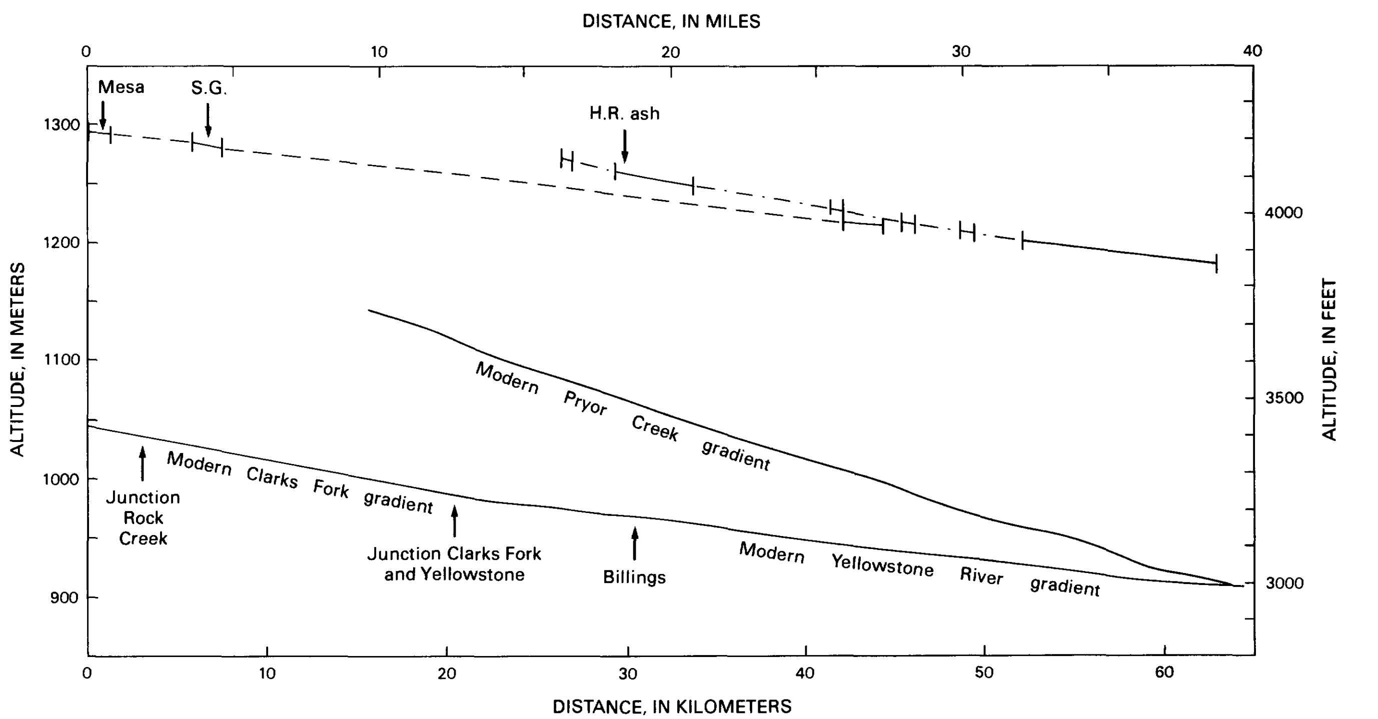


Figure 6. Comparison of Mesa and proposed equivalent terrace gradients to modern river gradients. H.R. ash, Huckleberry Ridge ash site; S.G., Silesia gravel (Ritter, 1975). Solid lines ending with vertical bars are actual terrace remnants; dash and dash-dot lines are inferred correlations. Terraces on dashed line projected to Clarks Fork and Yellowstone Rivers; those on dash-dot line projected to Pryor Creek.

deposits are not older than 10 ka (table 4), which is the age of the youngest deglacial deposits in West Yellowstone (Pierce and others, 1976).

The incision-rate age of 140 ka for the Bull Lake terrace confirms the correlation with Bull Lake deposits in West Yellowstone. The minimum incision-rate age of 90 ka falls within the time span of interglacial stage 5 (Shackleton and Opdyke, 1976), and

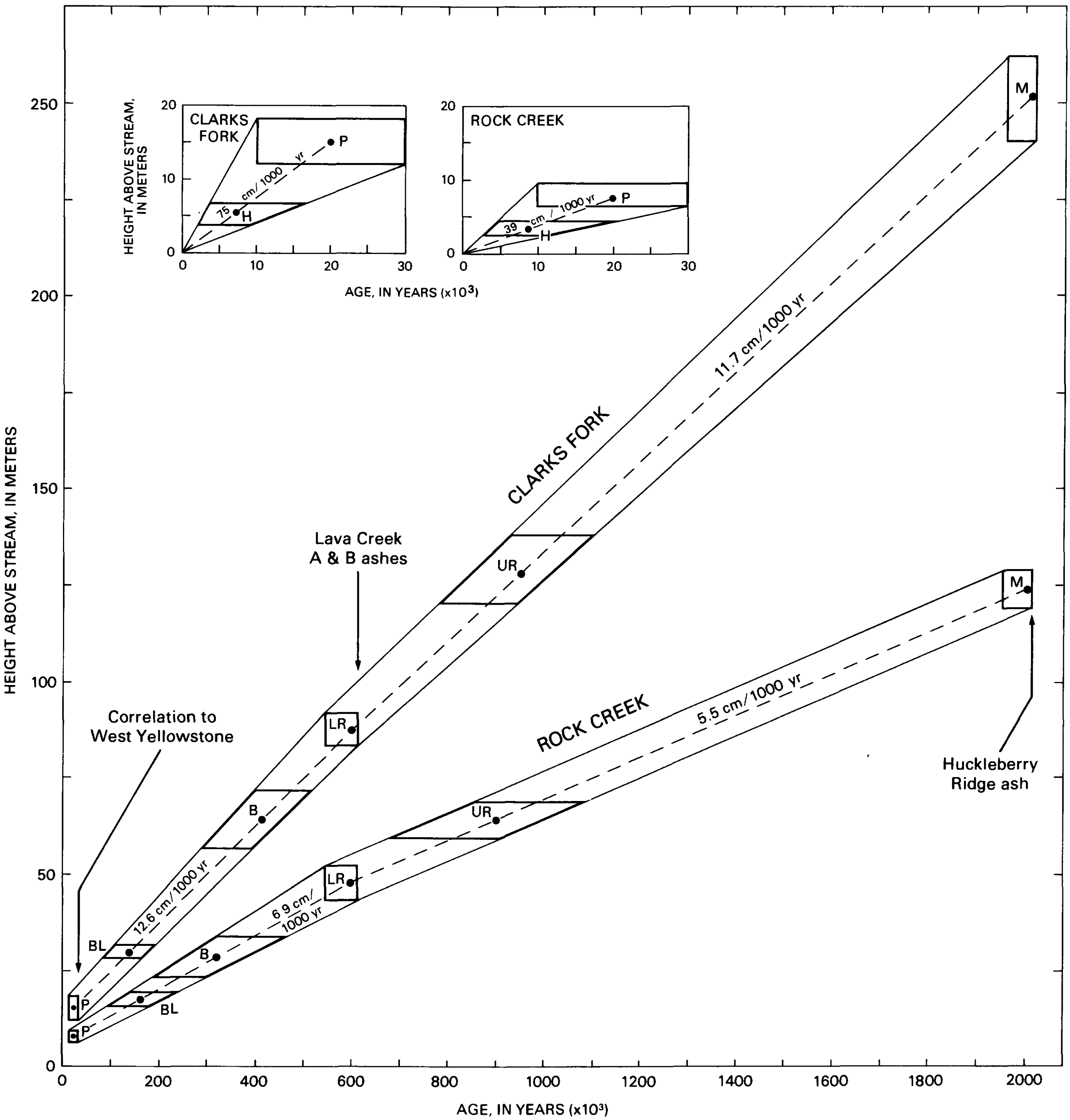


Figure 7. Graphs estimating ages of the Holocene (H), Bull Lake (BL), Boyd (B), and Upper Roberts (UR) terraces from mean terrace heights above the Clarks Fork and Rock Creek and ages of the Pinedale (P), Lower Roberts (LR), and Mesa (M) terraces. Dashed line is incision rate. Boxes around points for the Pinedale, Lower Roberts, and Mesa terraces show error limits of age from table 4 (horizontal lines) and height (± 1 standard deviation, vertical lines). Lines connecting outermost points of the boxes show the error envelope. Parallelograms show the age errors for other terraces, derived by projecting their height errors (± 1 standard deviation) horizontally to meet the lines of the error envelope (method adapted from Palmquist, 1979, 1983).

the maximum age of 200 ka is within the timespan of glacial stage 6. The best estimate age (table 4) of 120 ka for the Bull Lake terrace assumes that the terrace was incised within 10 ka after glacial activity ceased (130 ka in West Yellowstone).

The Boyd terrace is dated at about 415 ka from the Clarks Fork incision rate (fig. 7) and could range from 295 to 515 ka. Within this time span, Shackleton and Opdyke (1976) reported two glacial stages in the oxygen-isotope record from Pacific cores: stage 10 ends at about 347 ka, and stage 12 ends at about 440 ka (table 4). Using a core from the Atlantic and different calibration methods, van Donk (1976) found four glacial stages terminating within the timespan in question: stage 10 at about 300 ka, stage 12 at 360 ka, stage 14 at 400 ka, and stage 16 at 500 ka. Which glacial stage may correspond to the local glaciation that produced the Boyd outwash is unknown, and the age range given in table 4 cannot be narrowed.

The incision-rate age of the Upper Roberts terrace is 945 ka, and the range is 770 to 1,095 ka. The range is large because the terrace surfaces are poorly preserved. Van Donk (1976) showed three glacial stages in the Atlantic core that end within this timespan: stage 22 at about 780 ka, stage 24 at 870 ka, and stage 26 at 950 ka. The maximum incision-rate age of 1,095 ka falls within the very long interglacial stage 27, so the Upper Roberts terrace probably corresponds to a younger glacial stage. The oxygen-isotope record in this timespan is closely calibrated by the Jaramillo reverse-magnetization episode. Hence, the maximum age of the Upper Roberts is probably 950 ka (the end of glacial stage 26), and this coincides with the best estimate age of 945 ka from the incision rate.

The incision-rate method involves one major assumption: The long-term incision rate has remained constant between age control points. In the short term, this is false, because terraces are formed during stable or aggrading fluvial conditions and isolated by later incision. For example, the post-Pinedale incision rate (fig. 7) is six times faster than the pre-Pinedale, long-term incision rates.

Correlations of terraces were based on stratigraphy, terrace gradients, and heights above modern stream level. The terraces are generally well preserved, and these correlations are confidently made with the following exceptions: (1) The Lower Roberts terrace near Red Lodge may possibly be Upper Roberts, because the Upper Roberts terrace diverges from the Lower Roberts downstream and is not preserved upstream from the town of Roberts. (2) Soil RC-6 (fig. 2), which was sampled where the gradients of the Upper and Lower Roberts terraces converge, may be located on the Lower Roberts terrace rather than the Upper Roberts. (3) The Boyd terrace is absent between Roberts and Red Lodge, so the identity of that terrace at Red Lodge cannot be proved.

SOIL CLASSIFICATION

Soil morphology is commonly described with reference to the U.S. soil classification system (Soil Survey Staff, 1975). Unfortunately, soils of various ages within each chronosequence differ little when classified. All of the soils, except the youngest ones developed on Holocene deposits, have argillic horizons, and the basin soils and many transition soils have calcic horizons. However, none of the soils have horizons with sufficient clay or $CaCO_3$ to qualify them as very old soils (the prefix pale- indicates age) in the present taxonomy. The soil classification is more successful in indicating climatic differences between different chronosequences. Soil classifications that follow differ from those in the published soil survey for Carbon County, Mont. (Soil Conservation Service, 1975), primarily because data from the soil temperature probes (table 2) indicate that the transition soils and probably the mountain-front soils are presently under a mesic rather than a cryic soil temperature regime.

Soils in the mountain-front chronosequence are difficult to classify because the moisture regime borders on the udic and ustic, and the temperature regime borders on the cryic and mesic. These soils all have mollic epipedons (typical of soils developed under grass); under the present ustic moisture and mesic temperature regimes, the soils classify as Udic Argiustolls, with the exception of the Holocene soil which lacks an argillic horizon and is a Udorthentic Haplustoll.

Transition soils all have mollic epipedons and are under ustic moisture and mesic temperature regimes. Holocene soils lack argillic or calcic horizons and classify as Udic Haplustolls. Older soils have argillic horizons; depending on whether or not they also possess calcic horizons (variable in the transition zone), they are Udic Argiustolls (no calcic horizon) or Typic Argiustolls.

Basin soils all possess mollic and calcic horizons; most have argillic horizons, with the exception of the Holocene soils. Under the modern aridic and mesic regimes, the Holocene soils are Typic Calciorthids. The older soils are classified as Ustollic Haplargids with the exception of the Mesa soils. The height of the terrace remnant on which the Mesa soils were sampled may cause them to have a somewhat moister climate, although no site-specific climatic data are available. Thus, these soils may be Typic Argiustolls, like some of the transition soils.

The U.S. Soil Taxonomy does not adequately describe the Rock Creek soils under the reconstructed glacial climate (table 2). The mountain-front, transition, and basin areas would have had a pergelic temperature regime. The soil taxonomy has no provision for pergelic mollisols with argillic or calcic horizons.

CHRONOLOGIC DEVELOPMENT OF SOILS

Field properties of the Rock Creek soils change with increasing age (supplementary table 1). The thickness of A and B horizons and silt and clay contents increase with age. Colors redden and brighten or whiten and pale with time. Pedogenic $CaCO_3$ increases in basin soils. Soil structure does not show consistent changes with time, apparently because of the gravelly nature of the parent material. These and other trends are studied by converting verbal descriptions of soil properties to numerical quantities using Harden's (1982b) soil development index.

The vertical distribution of index properties in soil profiles shows patterns of soil development with time in different climates (figs. 8 and 9). Textural fining due to accumulation of silt and clay (total texture) increases in amount and depth in the profiles with time in all three chronosequences, but the fines are concentrated at lesser depths in drier climates. Rubification (reddening and brightening) increases in amount and depth with age in mountain-front soils. In contrast, the colors of calcareous horizons of basin and transition soils pale and lighten (Harden and Taylor, 1983). Values for pH decrease in mountain-front soils, but increase at depth in drier soils. The profile index, which weights all component properties equally[3], shows that most development of soil properties is concentrated in the A and B horizons.

This study extrapolates or limits all soil depths to 250 cm when calculating property values using the Harden (1982b) index, in order to minimize the variability caused by different sampling depths in the different excavations. Index values summed over the profiles of young soils may be too large, because values in the lowest horizon sampled (often 100-150 cm) are extrapolated to 250 cm. In particular, the rubification values for the Holocene and post-Pinedale mountain-front soils are probably too large, as is one pH value (post-Pinedale soil RC-15, fig. 2). However, changes in color and in pH extend to the bottom of older soils; hence, profile sums for the color and pH indices may be minimum values for development in older soils.

The rate of development of index properties varies in different climates when the best estimate surface ages in table 4 are used. Unless specifically mentioned as omitted, all soils listed in supplementary table 1 are included in the regression equations. Figures in the following discussion display values considered to be anomalously large, but employ the probable minimum values in regression equations. The significance levels of $\underline{r}^2$ (coefficient of determination) values are determined from tabled values for F ratios at specified degrees of freedom, which varies depending on N, the number of samples used in each regression (Davis, 1973).

Mountain-Front Soils

Several soil properties (Harden, 1982b) change with time in mountain-front soils, including rubification (reddening and brightening due to iron oxide formation), melanization (darkening due to accumulation of organic matter), pH lowering, clay films, and total texture (changes in silt and clay content as reflected in texture, corrected with laboratory data, plus wet consistence). Values for the post-Mesa soil RC-28 (fig. 2) have been omitted from regression calculations because it appears to have been affected by erosion.

[3]Only selected component properties of the profile index are shown on figures 8 and 9.

The individual soil properties and the profile index (Harden, 1982b) calculated from the combined properties generally show logarithmic (log) rates of increase with time (fig. 10). Regressions of melanization, total texture, rubification, clay films, and the profile index with the best estimate soil ages (table 4) are significant at the 1 percent level of confidence; pH lowering with time is irregular and is not significant at the 5 percent level. Rubification, total texture, and clay films are related to near-surface weathering phenomena, and they are largest in B horizons (fig. 8). Melanization and pH lowering are related to accumulation of organic matter, so they are largest in A and upper B horizons (fig. 9).

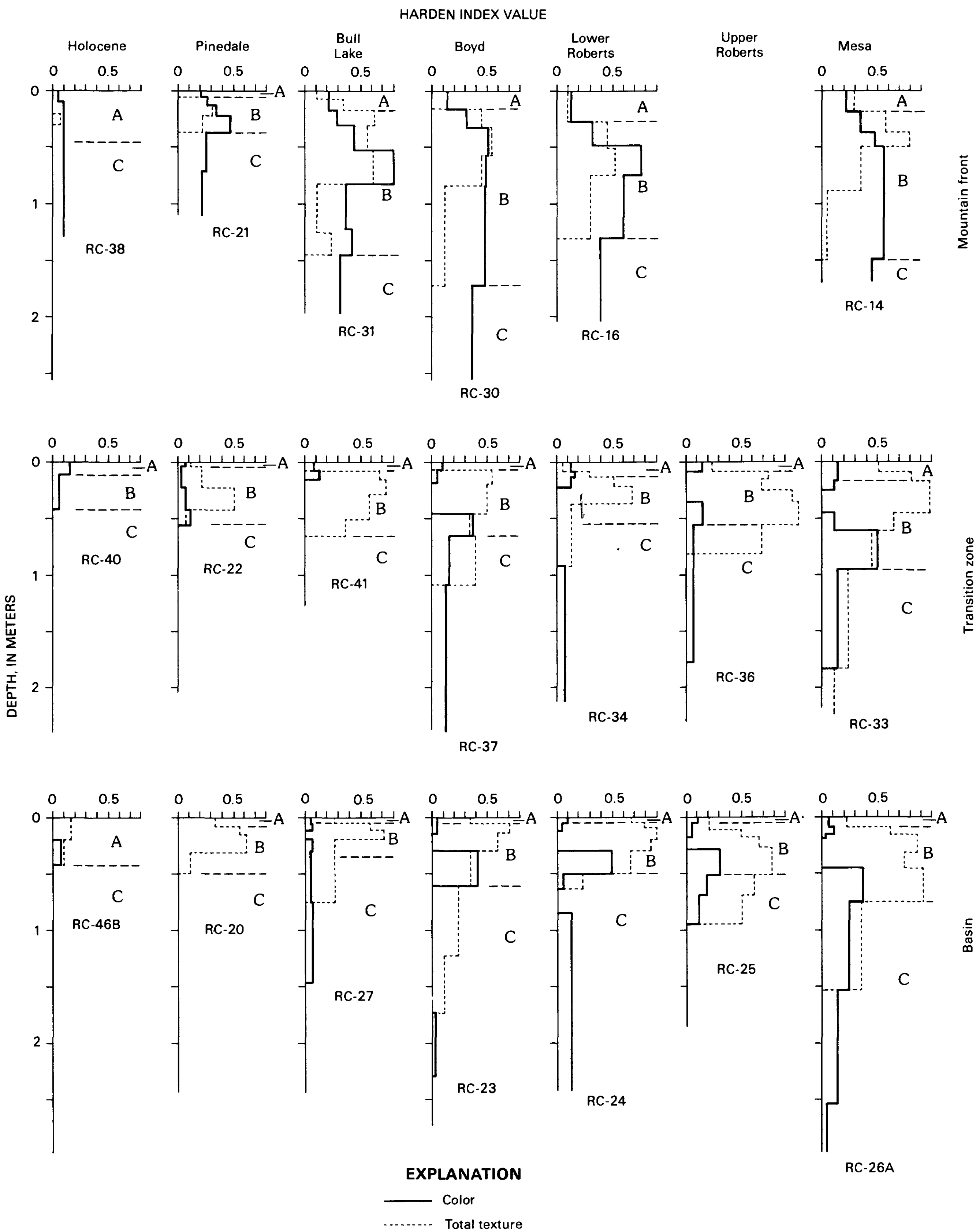
Petrographic thin sections indicate that silt and clay accumulate by both translocation and weathering in situ in the mountain-front soils. Oriented argillans of clay on sand grains (Morozova, 1964; Dumanski, 1969) are deposited by percolating water; they show translocation of clay particles in the Rock Creek soils (fig. 11), and they increase in thickness and abundance with time through soils on the Bull Lake terrace (120 ka). Older soils have thicker but less well oriented argillans and other masses of clay in the matrix, indicating that translocated clays and other particles weather in situ with time.

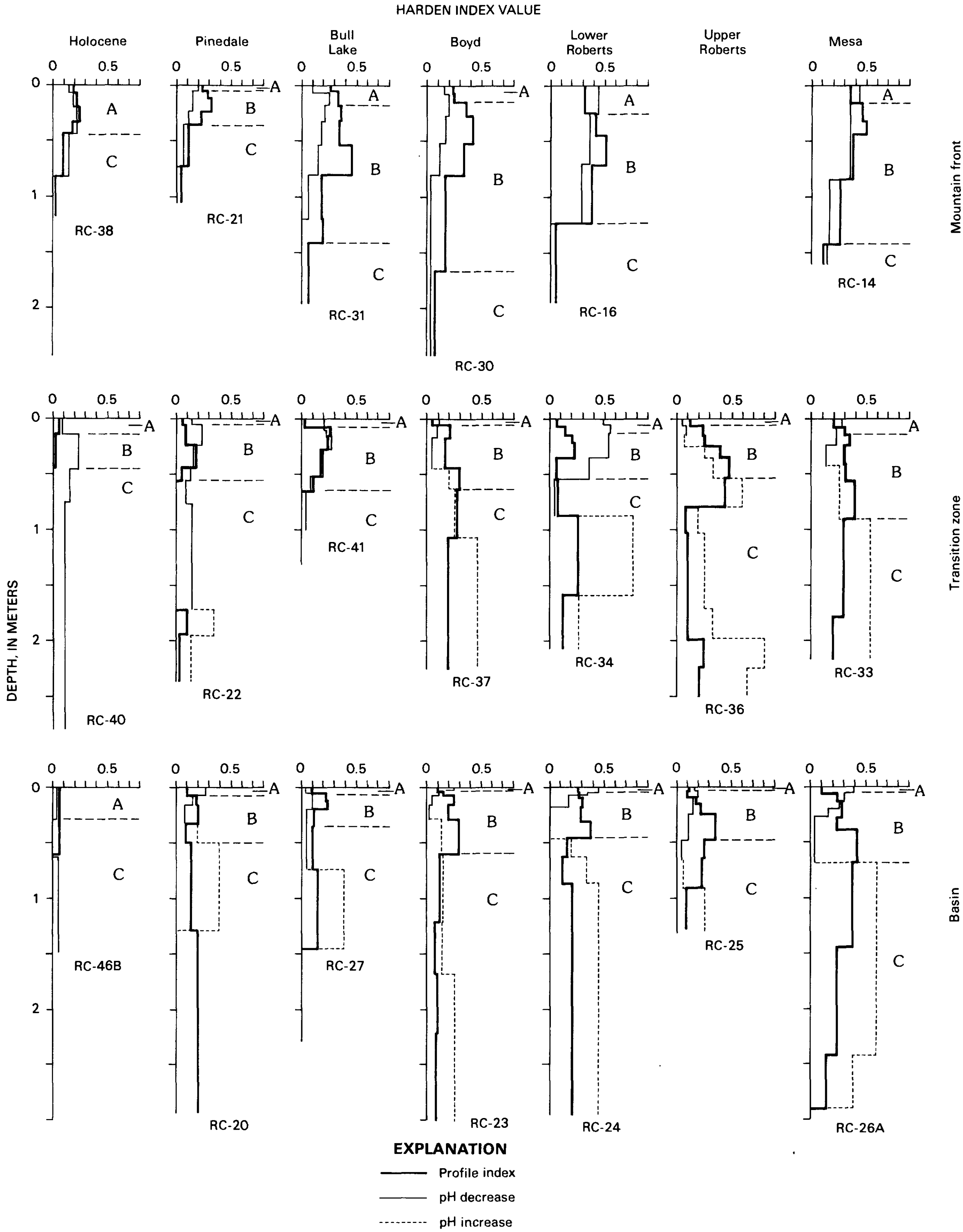
The logarithmic property-time relations (fig. 10) indicate that initial weathering is rapid in mountain-front soils. Stones weather to grus quickly; even post-Pinedale soils have 10-15 percent grusified clasts in the B horizon. The rapid disintegration may be due to hydration and expansion of biotite grains (Wahrhaftig, 1965). In petrographic thin sections, expanded biotite flakes occur in soils as young as 20 ka. Concomitant release and oxidation of iron from the biotite probably accounts for the rapid rubification of the soils, with hues reaching 7.5 YR and chromas of 6 in post-Pinedale soils. Only the post-Mesa soil and the post-Bull Lake soil have redder hues.

Basin Soils

Different soil properties change with time for soils forming in the semiarid climate in the basin (figs. 8 and 9). Values of pH decrease near the surface where organic matter is concentrated, but increase at depth (fig. 9) due to the presence of $CaCO_3$ (abrasion pH of $CaCO_3$ is 8.0; Stevens and Carron, 1948). Total texture increases with time, but clay films do not develop in the basin soils. Although thin sections show that clay translocation has occurred (see fig. 20),

Figure 8. Rubification (mountain-front soils), color paling and color lightening (transition and basin soils), and total-texture (all soils) indices (Harden, 1982b, and Harden and Taylor, 1983) for selected soils on Rock Creek, showing changes with depth, time, and climate. Numbers indicate soil profiles (see supplementary tables 1 and 2). Dashed lines show boundaries between soil horizons A, B, and C. K horizons are included with B horizons in some transition and basin soils. See figure 2 for location of soil profiles.


HARDEN INDEX VALUE
Holocene
Pinedale
Bull Lake
Boyd
Lower Roberts
Upper Roberts
Mesa
DEPTH, IN METERS
Mountain front
Transition zone
Basin
RC-38
RC-21
RC-31
RC-30
RC-16
RC-14
RC-40
RC-22
RC-41
RC-37
RC-34
RC-36
RC-33
RC-46B
RC-20
RC-27
RC-23
RC-24
RC-25
RC-26A
EXPLANATION
Color
Total texture


HARDEN INDEX VALUE
Holocene
Pinedale
Bull Lake
Boyd
Lower Roberts
Upper Roberts
Mesa
0
0.5
0
1
2
DEPTH, IN METERS
A
B
C
RC-38
RC-21
RC-31
RC-30
RC-16
RC-14
Mountain front
RC-40
RC-22
RC-41
RC-37
RC-34
RC-36
RC-33
Transition zone
RC-46B
RC-20
RC-27
RC-23
RC-24
RC-25
RC-26A
Basin
EXPLANATION
Profile index
pH decrease
pH increase

macroscopic clay films on ped faces are not well preserved. Accumulation of pedogenic $CaCO_3$ causes soils to pale and lighten with time (Harden and Taylor, 1983). If iron oxidation is occurring in the basin soils, it is masked by $CaCO_3$; as a result, rubification does not increase with time. Melanization does not increase because organic matter is rapidly oxidized in a dry climate.

The profile index and the properties of total texture, color paling and color lightening, and pH increase with time; the regressions are significant at the 1 percent level of confidence (fig. 12). Values for the post-Mesa soil RC-26B (fig. 2) were omitted because this soil appears eroded. In addition, the post-Pinedale soil RC-20 has an anomalously high value of pH increase and consequently a high value for the profile index (fig. 12B), possibly caused by local irrigation. Values for this soil were omitted from the pH and profile index regressions.

The regressions with age of the indices for pH increase and texture, and the profile index, appear to be equally good with either log or linear time (fig. 12). In general, the log solutions tend to overestimate values of these indices for soils in the 10^3-10^5-year age range and to underestimate values for the post-Mesa soils. The linear solutions fit the property values of the soils older than 10^5 years well, but overestimate property values for the younger soils. Assuming that the best estimate soil ages are correct, basin soils may initially develop at log rates, but later develop at linear rates.

Color paling and color lightening are clearly best explained by a linear time function (fig. 12A). This property reflects accumulation of $CaCO_3$ and is better related to soil age than is the quantity of pedogenic $CaCO_3$. Profile weights of pedogenic $CaCO_3$ (fig. 13) increase with age of basin soils up to about 400 ka, but the relationship is not significant for older soils.

Eolian contributions of calcareous dust are important in the development of basin soils. The increase in total texture with time may be due at least in part to additions of eolian silt (supplementary tables 1 and 2). The A and B horizons of most basin soils are loams or silt loams rather than sandy loams or sandy clay loams characteristic of mountain soils. Formation of calcic soils in noncalcareous parent materials is commonly attributed to atmospheric additions of $CaCO_3$, including calcareous dust and Ca^{2+} contained in precipitation (for example Gardner, 1972; Bachman and Machette, 1977; Gile and Grossman, 1979; Machette, 1985). Because the Rock Creek alluvium contains almost no calcareous detritus, accumulation of $CaCO_3$ in the soils with time must result from atmospheric additions.

The composition and amount of dust collected for one year in a trap near Joliet (fig. 2) suggests that there are significant additions of calcareous eolian dust to the semiarid Rock Creek soils (table 5). Infall of mineral particles (nonsalt, nonorganic fraction) is about 15×10^{-4} $g/cm^2 \cdot yr$. Even if the measured amount was 10 times the amount away from plowed fields, this input would be significant. $CaCO_3$ is added at the rate of 0.3×10^{-4} $g/cm^2 \cdot yr$. This $CaCO_3$ rate is an order of magnitude less than modern dustfall rates near Las Cruces, N. Mex. (Gile and Grossman, 1979), the Holocene rate calculated for southern California (McFadden and Tinsley, 1985), and the Pleistocene rate

Figure 9. Profile and pH indices (adapted from Harden, 1982b) for selected soils on Rock Creek, showing changes with depth, time, and climate. Numbers indicate soil profiles (see supplementary tables 1 and 2). Dashed lines show major boundaries between soil horizons A, B, and C. K horizons are included with B horizons in some transition and basin soils. See figure 2 for location of soil profiles.

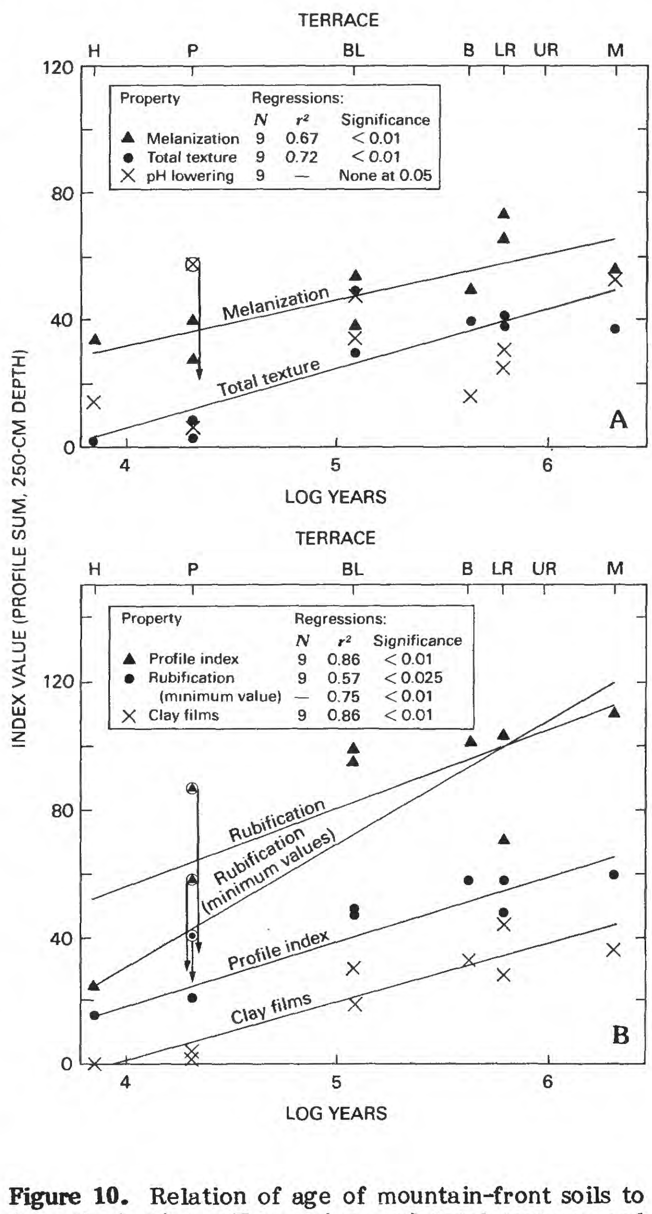
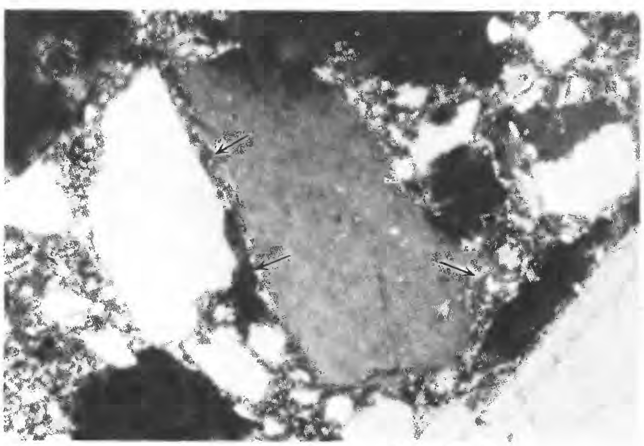


Figure 10. Relation of age of mountain-front soils to A, melanization, pH lowering, and total texture; and B, profile index, rubification, and clay films (Harden, 1982a). Straight lines are regressions on log age (table 4). Circled data points represent questionable values derived by large extrapolations to 250 cm depth; arrows extend down to minimum index values for these points. H, Holocene; P, Pinedale; BL, Bull Lake; B, Boyd; LR, Lower Roberts; UR, Upper Roberts; M, Mesa; N, number of data points.

calculated for areas of Utah and New Mexico (Machette, 1985). Lower rates at Joliet are probably due to the lack of extensive calcareous deposits upwind to the west and north.

Rates of accumulation of $CaCO_3$ in basin soils, calculated from profile weights of $CaCO_3$ (fig. 13 and supplementary table 7), range from 0.11 to 1.5×10^{-4} $g/cm^2 \cdot yr$ for soils older than 400 ka, to 1.0 to 5.5×10^{-4} $g/cm^2 \cdot yr$ for post-Holocene and post-Pinedale soils. The lower rates for older soils probably reflect episodes of $CaCO_3$ solution during glaciations. The higher rates calculated for the younger soils represent the average rate of accumulation during the drier Holocene period (note that the amount of pedogenic $CaCO_3$ is similar for post-Holocene and post-Pinedale soils, fig. 13). This disparity between rates of $CaCO_3$ accumulation for older and younger soils is similar to that found by Machette (1985) in New Mexico and Utah.



A 0 1 MILLIMETER

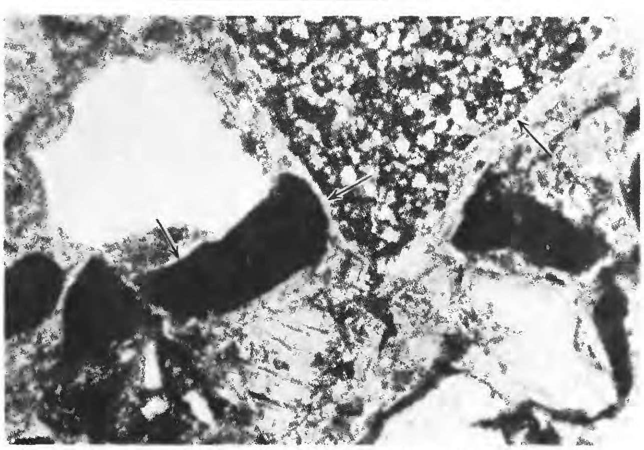


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Figure 11. Photomicrographs (crossed nicols) of argillans coating grains in mountain-front soils. A, Post-Pinedale soil has thin discontinuous argillans, best seen in bright bands (arrows) around large gray quartz grain in left center. B, Post-Boyd soil has thicker, continuous argillans (arrows).

Linear development rates for the older basin soils are contrary to results obtained by workers in warmer, more moist climates (Harden, 1982a and b; Colman and Pierce, 1981; Birkeland, 1984, p. 204 and 225), where rates were found to be logarithmic or exponential. Bockheim (1980) obtained logarithmic trends with time for soils formed in climates ranging from tropical rainy to cold desert; his study, however, used maximum values in each profile, rather than summations over the total profile depth. Muhs (1982) expressed soil properties in an arid xeric climate as profile summations and found linear trends with time; these soils probably received considerable dust influx. I believe that linear trends with soil age of index

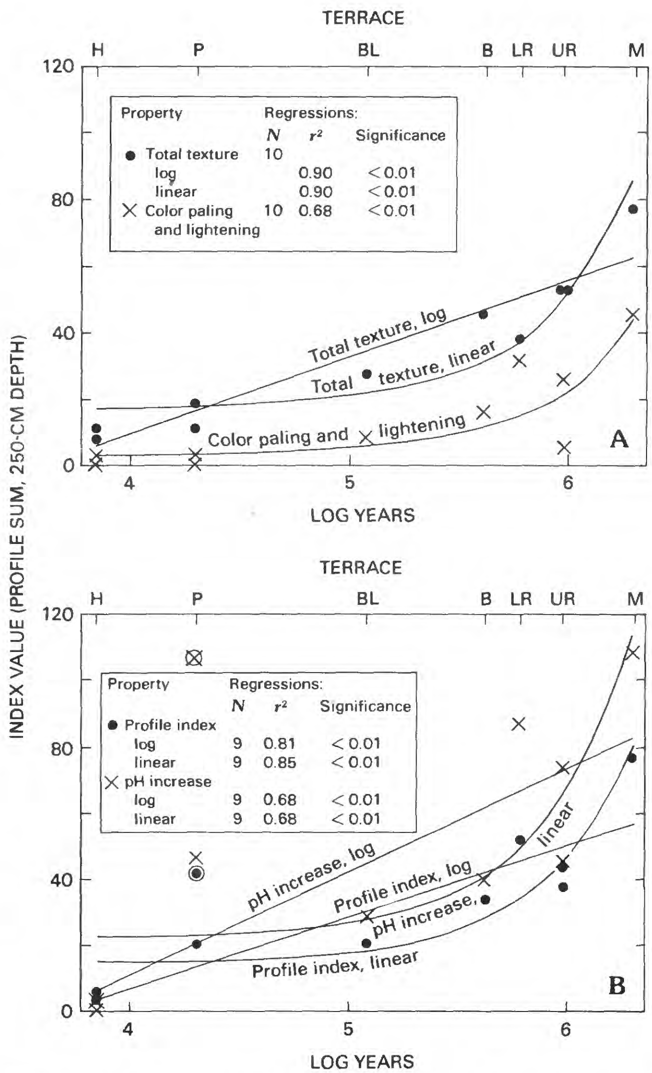

Figure 12. Relation of age of basin soils to A, total texture and color paling and color lightening; and B, profile index and pH increase (adapted from Harden, 1982a, and Harden and Taylor, 1983). Straight line is regression on log age; curved lines are regressions on age (table 4). Circled data points represent questionable values. H, Holocene; P, Pinedale; BL, Bull Lake; B, Boyd; LR, Lower Roberts; UR, Upper Roberts; M, Mesa; N, number of data points.

values based on field criteria for the basin soils of Rock Creek may best be explained, not by weathering phenomena, but by cumulative additions from atmospheric sources to the soil profiles.

Transition Soils

Transition soils have time-dependent properties that are most similar to those of basin soils. Soils on the older terraces of the transition chronosequence are located within 15 km of the mountain front (fig. 2), yet there are no significant trends of rubification, melanization, and clay films with time in these soils.

The profile index and the properties of total texture, pH, and color paling and color lightening increase with time (fig. 14). Data for the post-Mesa soil RC-8, located on the eroding end of a terrace remnant, has not been included in the regression calculations. Soil RC-32 was sampled at the edge of a lawn and appears anomalously well developed because of irrigation and fertilization; it was also omitted. The rates of property development are similar to those of basin soils (compare figs. 12 and 14). Values of r^2 for pH, total texture, and the profile index are significant at the 1 percent level of confidence. Color paling and color lightening and profile weight of pedogenic $CaCO_3$ (fig. 13) are not as well related to time as they are in basin soils, as would be expected in soils that have undergone periodic precipitation and dissolution of secondary $CaCO_3$.

Values of pH appear to reflect a transitional state between mountain-front and basin soils (figs. 9

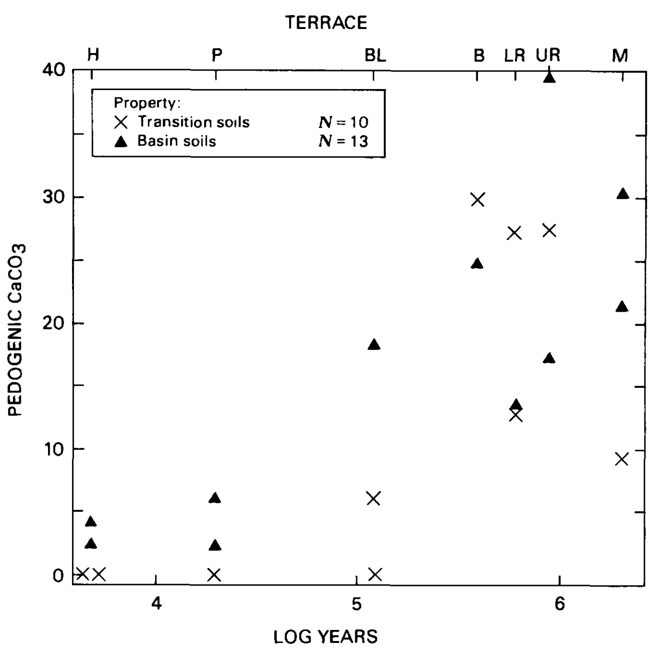

Figure 13. Relation of ages (table 4) of basin and transition soils to profile weights of pedogenic $CaCO_3$ (in grams per square centimeter in 250 cm of soil). H, Holocene; P, Pinedale; BL, Bull Lake; B, Boyd; LR, Lower Roberts; UR, Upper Roberts; M, Mesa; N, number of data points.

Table 5. Composition and particle size of eolian dust from dust trap

[First column under major oxides gives percent as measured on the nonsalt silt-plus-clay fraction. Second column gives recalculated percent oxides assuming that all $CaCO_3$ in the trap was contained in the silt-plus-clay fraction. See figure 2 for sample location]

Air-dry weight (g)	1.7047
Percent of total sample	
organics	19.0
$CaCO_3$	1.5
mineral matter	79.5
Percent of mineral matter fraction	
sand	21.0
silt	49.0
clay	30.0
Flux rate (10^{-4}g/cm^2/yr)	
mineral matter	15.6
$CaCO_3$	.3

Percent of silt-plus-clay fraction

Oxide	Measured	Recalculated
SiO_2	56	55
Al_2O_3	11.9	11.7
Fe_2O_3	4.6	4.5
MgO	1.5	1.5
CaO	1.6	1.6
Na_2O	3.1	3.1
K_2O	3.0	3.0
TiO_2	.53	.52
MnO	.027	.027
ZrO_2	.035	.034

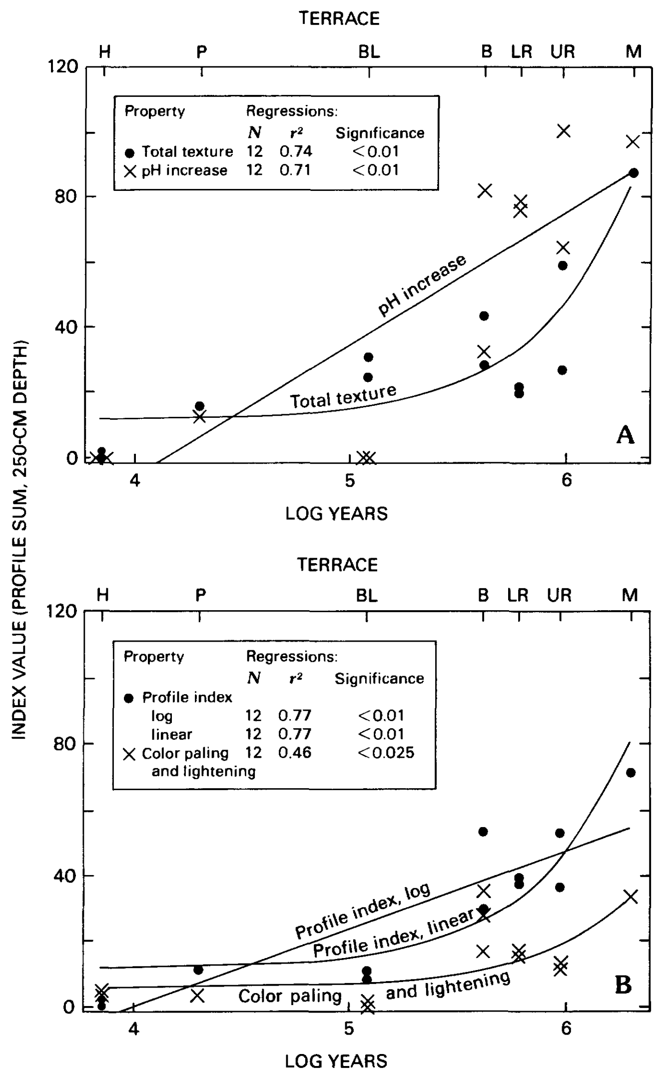

Figure 14. Relation of age of transition soils to A, total texture and pH increase; and B, profile index and color paling and color lightening (adapted from Harden, 1982a, and Harden and Taylor, 1983). Straight lines are regressions on log age; curved lines are regressions on age (table 4). H, Holocene; P, Pinedale; BL, Bull Lake; B, Boyd; LR, Lower Roberts; UR, Upper Roberts; M, Mesa; N, number of data points.

and 14A). Values of pH increase with time in the lower soil horizons, similar to pH trends in the basin soils. However, pH decreases with age in the upper horizons of transition soils, similar to pH in mountain-front soils.

The profile index for transition soils develops at a rate comparable to that for basin soils (figs. 12B and 14B), and values for the two groups (77 for transition and 72 for basin) are about the same for the oldest post-Mesa soils. As for basin soils, the relation of the profile index to estimated soil age is equally well expressed as a log or a linear function. The linear function appears to fit the profile-index values better than the log function, except that the linear function overestimates values for the Holocene soils.

The similarity between (1) the types of properties that have significant relations to time and (2) the development rates for transition and basin soils suggests that development of transition soils is controlled by the same processes that affect basin soils: eolian additions of $CaCO_3$ and dust. If this is so, the amount of eolian material added through time may be similar in both chronosequences. Although $CaCO_3$ is flushed periodically from the transition soils, the pH increase related to the additions of $CaCO_3$ appears less affected by flushing. The additions of silt and clay from eolian dust are not affected by climatic changes.

Chronologic Summary

Six of the seven soil properties examined consistently correlate with age of the soils. Only pH-lowering of mountain-front soils does not have a statistically significant relationship with time. Change in pH is caused by very different processes in each chronosequence: pH lowering due to organic matter accumulation in mountain-front and transition soils, versus pH increase due to accumulation of pedogenic $CaCO_3$ in basin and transition soils. Total texture and color changes are also controlled by different processes in different climatic regimes. The texture of mountain-front soils fines at log rates, probably controlled by near-surface weathering processes, whereas textures of transition and basin soils older than 20 ka fine at linear rates, probably caused by influx of eolian dust. Modern dust and the increasing amounts of $CaCO_3$ and silt in basin soils with time support cumulative additions from atmospheric sources. Log increases in rubification and melanization of mountain soils are related to weathering, but eolian $CaCO_3$ influx probably causes linear increases in color paling and color lightening.

These findings contrast with those of Harden and Taylor (1983). They found that rubification, dry or moist consistence, and total texture increased at log rates for soils in udic, xeric, and aridic moisture regimes, although texture (their fig. 4A) appears to exhibit more of a linear trend with time. Regression coefficients for linear time were not given in their study. In this study, rubification does not correlate with time for semiarid soils, and texture in these soils appears better related to linear than to log time. Perhaps rubification does not develop in Rock Creek basin soils because the climate there is cool and semiarid, rather than hot and semiarid as in the Las Cruces, N. Mex. area used in the Harden and Taylor study. Color paling and color lightening have strong relations with log time in their study, whereas these two properties combined correlated best with linear time in this study.

Harden and Taylor (1983) also showed that soils from udic, xeric, and aridic moisture regimes developed at similar rates when they were compared using profile indices calculated from the four best time-related properties in each chronosequence. There are both similarities and differences among profile indices of the three Rock Creek chronosequences (fig. 15). The logarithmic functions for the three chronosequences have similar slopes, although profile indices on the average are smaller for the transition and basin soils than for the mountain-front soils. Harden and Taylor (1983) also noted that aridic soils tended to develop at a similar rate but with lower values than soils in moister climates. The rates of development are similar enough that when profile indices for soils from all the chronosequences are regressed with soil ages, the $\underline{r}^2$ value of the log function is 0.71. However, when the Holocene soils of Rock Creek are omitted, the best-fit time functions for the drier soils are linear ones, and they are nearly identical for the basin and transition chronosequences.

In conclusion, although the profile index appears to develop at similar rates for the three Rock Creek chronosequences when regressed against log time, there are also important differences. Caution should be used in applying linear or log curves to weathering

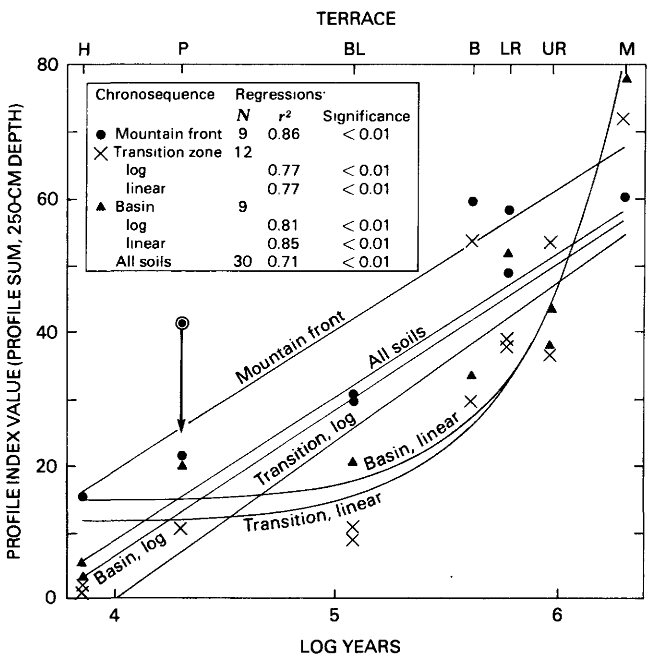

Figure 15. Relation of age of the three soil chronosequences individually and as a group to profile index. Straight lines are regressions on log age; curved lines are regressions on age (table 4). Circled data point represents questionable value; arrow extends down to minimum index value for this point. H, Holocene; P, Pinedale; BL, Bull Lake; B, Boyd; LR, Lower Roberts; UR, Upper Roberts; M, Mesa; N, number of data points.

data in order to estimate soil age. For example, Colman and Pierce (1981) assumed logarithmic rates of weathering-rind formation in order to estimate the ages of till deposits in the Western United States. Their arguments were well founded, but these arguments should not necessarily be extrapolated to soil-forming processes.

CLIMATIC DEVELOPMENT OF SOILS

Time-related properties of soils along Rock Creek are strongly influenced by the local climate. Different properties change with time in mountain-front (moist) and basin (semiarid) soils. The transition soils, rather than reflecting the combined attributes of mountain-front and basin climates, resemble the basin soils. Either the modern interglacial climate of the transition zone has eliminated morphologies that are characteristic of a glacial climate, or glacial climatic changes may not have altered greatly the style of soil formation along Rock Creek. If the changes had been effective, transition soils should display time-related characteristics of mountain-front soils, such as melanization and clay films, as well as characteristics of basin soils. Soil properties within each chronosequence can be used to examine the local effects of climatic change and to determine whether the reconstructed glacial climate is reasonable.

Mountain-Front Soils

Mountain-front soils on Rock Creek have developed under relatively moist, cool or cold climates (fig. 5). Under a glacial climate, the soil moisture regime probably changed from ustic to udic, and surplus water available for leaching and deep percolation probably doubled from 160 to 335 mm/yr (assuming that glacial precipitation was equal to the modern level). Actual leaching of the soil was most likely concentrated in the active zone above permafrost in months when soil temperatures were above freezing.

Depth of pedogenic clay is related to the depth of water movement in a soil, and may vary with climate (Rutter and others, 1978; Nettleton and others, 1975). Pedogenic clay depth (defined here as depth to top of first C horizon) can be related to climate and soil age by plotting clay depth in each soil on a diagram showing modern water movement at Red Lodge (fig. 16; method of Arkley, 1963). Clay depths are calculated in units of yearly water penetration based on the available water-holding capacity of each horizon, in order to equalize the effect of different soil textures on permeability. However, the increase of silt and clay in profiles with time can change clay depth. Fine-grained soils have greater water-holding capacity than do coarse sandy soils. Thus, pedogenic clay moved to a given wetting depth early in soil development may appear at greater wetting depths with time because of accumulation of fines near the surface.

Post-Pinedale and Holocene soils have clays at shallower wetting depths than do older soils (fig. 16). This difference is probably related to climate, because depths do not continue to increase with age in the older soils. Post-Pinedale and Holocene soils have mainly formed under an interglacial climate, whereas older soils have formed during both dry interglacial and moist glacial periods. Greater depth of pedogenic clay in the post-Pinedale soil than in the Holocene soil may reflect the greater amount of fines accumulated near the surface of the older soil.

The similarity of pedogenic clay depths for older soils implies that pre-Pinedale glaciations were no more moist than the Pinedale glaciation, when clays were moved to a wetting depth of 10 cm (fig. 16). If older glaciations had been more moist, soils older than the post-Bull Lake soil would have pedogenic clay at wetting depths greater than 10 cm. Drier previous glaciations are possible, because high moisture levels during Pinedale time could have affected the position of pedogenic clay in all older soils. However, the greater extent of pre-Pinedale till deposits (fig. 2) suggests that these glaciations were probably not drier than the Pinedale glaciation.

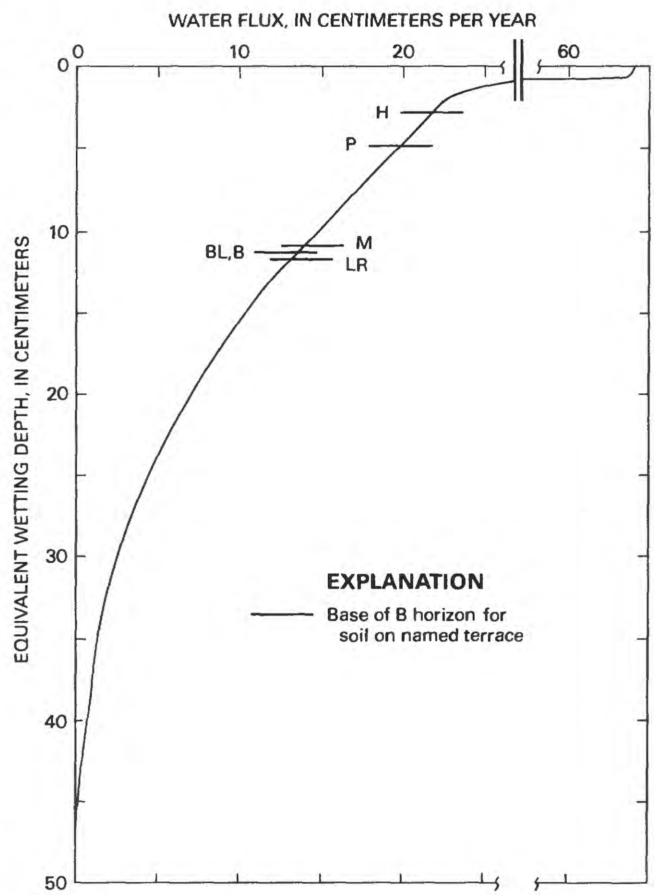

Figure 16. Water movement and pedogenic features of mountain-front soils. Average yearly water movement (curved line) calculated for 82-year record at Red Lodge using Arkley's (1963) method. Pedogenic clay depth defined as base of B horizon and expressed in centimeters of wetting depth of yearly precipitation by estimating available water-holding capacity for each horizon from textural data (Salter and Williams, 1967).

Transition Soils

Transition soils show abundant evidence of having formed under variable climate. Soils of drier climates that accumulate $CaCO_3$ typically have horizons of $CaCO_3$ enrichment with smooth upper boundaries, reflecting the average depth of transport of $CaCO_3$ in solution. $CaCO_3$ horizons of transition soils always have wavy, irregular tops that suggest periodic dissolution of $CaCO_3$ (fig. 17A). Near the boundary between calcic and noncalcic soils, pedogenic $CaCO_3$ occurs in patches having a random-appearing distribution on continuously exposed faces in gravel pits. Locally, $CaCO_3$ fills cracks in stones as it does in the more highly calcareous basin soils, suggesting a formerly more extensive $CaCO_3$ horizon. Petrographic thin sections of peds (fig. 17B) also reveal evidence of dissolution and reprecipitation of pedogenic $CaCO_3$. Unfortunately, the fluctuations of moisture in these soils were apparently sufficient to wipe out much of the evidence of older wet and dry cycles.

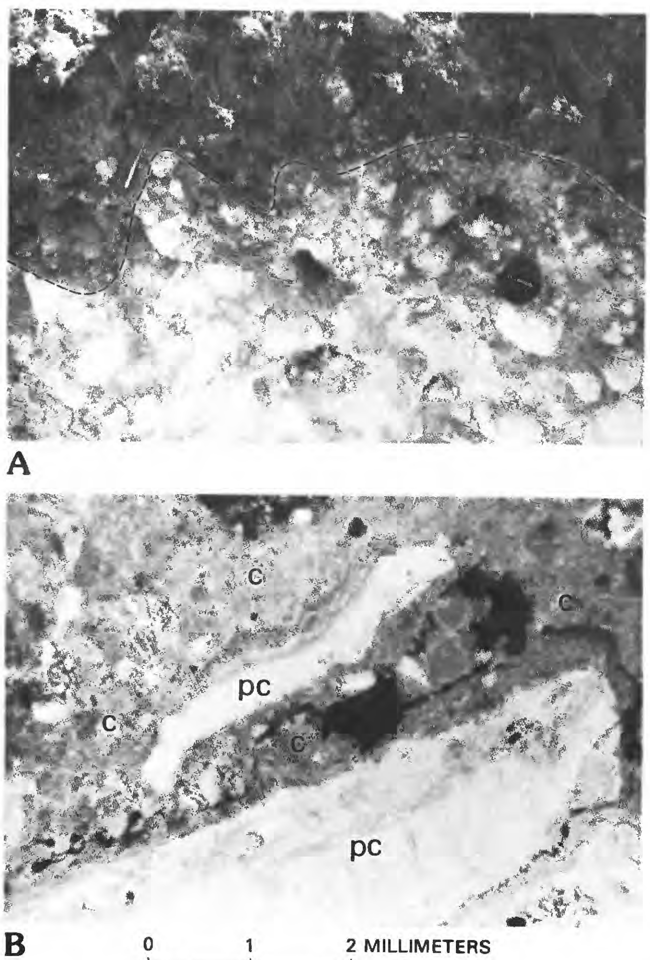

Figure 17. Evidence of periodic $CaCO_3$ dissolution in transition soils. A, Wavy top of light-colored $CaCO_3$ horizon (dashed line) reflects dissolution of formerly horizontal upper boundary. Lens cap is 5 cm in diameter. B, Photomicrograph shows lenticular pebble coats (pc) of $CaCO_3$ broken away from the pebbles and reworked into the soil matrix. New, finer grained $CaCO_3$ (c) is precipitating in matrix around pebble coats.

The position of the calcic-noncalcic soil boundary[4] shifts mountainward with increasing terrace age up to the lower Roberts terrace (figs. 3 and 18). The Boyd and Upper Roberts terraces are not preserved in the critical area. The calcic-noncalcic soil boundary on the Boyd terrace was estimated from the appearance of soil RC-11 on the Boyd remnant with calcic soils nearest the mountains at the town of Roberts.

Several possible explanations for the shifting calcic-noncalcic soil boundary are based on differences in climate among the terraces: (1) If rainfall decreases away from the river bottom, older terraces that are farther from Rock Creek may show $CaCO_3$ closer to the mountain front. However, the calcic-noncalcic soil boundary on the Lower Roberts terrace occurs where the terrace is actually adjacent to the valley near Red Lodge. (2) Rainfall may decrease with increasing height above the creek. If that were so, the observed correspondence of the calcic-noncalcic soil boundaries on the Lower Roberts and Mesa terraces should not occur (fig. 18). More significantly, such a trend is contradicted by the orographic effect of increasing rainfall with altitude. (3) Less snow may accumulate on higher, more exposed terraces, leaving them drier. Again, the boundaries on the Lower Roberts and Mesa terraces should not be the same in this case, but such a phenomenon might account for the boundary shift on younger terraces.

The most common explanation for changes in calcic-noncalcic soil boundaries elsewhere is based on climatic change. Dan and Yaalon (1971) attributed to past climatic change the interfingering relationships of red noncalcareous paleosols and brown calcareous paleosols on loess. Richmond (1972) presented a plot similar to that in figure 18 for several areas in the Rocky Mountains and suggested that the higher calcic-noncalcic soil boundaries on older deposits formed during interglacial periods that were more arid than the present. If this explanation is applied to Rock Creek, it indicates a regular increase in aridity of progressively older interglacials during the past 600,000 years (fig. 18). Two lines of circumstantial evidence suggest weaknesses in this hypothesis. First, pedogenic clay in mountain-front soils and the extent of till deposits suggests that the most recent glaciation was about as wet as those in the past. The climatic change hypothesis would require older interglacials to be drier. Trends in glacial climates need not be linked necessarily to trends in interglacial climates, however. Second, the pedogenic $CaCO_3$ in older soils near the mountain front is powdery and is probably easily dissolved. Because moisture from this

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[4] The calcic-noncalcic soil boundary is defined as the geographic position where pedogenic $CaCO_3$ first appears going downstream on each terrace.

or previous glaciations was capable of moving clay to the same depth in all mountain-front soils, why would not soluble $CaCO_3$ occur at similar depths and distances from the mountain front in all ages of transition soils?

A last hypothesis for the shifting calcic-noncalcic soil boundary is based on the morphology of $CaCO_3$ in soils near the boundary. Isolated patches of $CaCO_3$ occur in these soils that in general are free of pedogenic $CaCO_3$. $CaCO_3$ that accumulates close to the boundary during a dry interglacial episode may not be entirely dissolved in the following glaciation, being preserved in favorable spots where the soil microenvironment is relatively dry. These remnants can then act as nuclei in the next dry period and permit $CaCO_3$ to build up more rapidly closer to the mountain front than in the previous interglacial. Alternatively, the calcic-noncalcic soil boundary may be related to age-dependent textural fining: $CaCO_3$ precipitated at a given wetting depth may be protected from subsequent leaching by accumulation of near-surface fines that increase the soil AWC (available water-holding capacity). With time and multiple climatic changes, the boundary is pushed closer to the mountain front without requiring an overall change in the average climate. More work is needed to verify which of these two hypotheses--progressively drier interglacials in the past or age-related boundary shift--is correct.

The relation of modern water movement on terraces at Roberts to wetting depths of $CaCO_3$ and pedogenic clay provides insight into past climatic changes (fig. 19). Depth to the shallowest occurrence of $CaCO_3$ and to continuous horizons of $CaCO_3$ shows no trends with soil age. This is not surprising, given the changing position of the calcic-noncalcic soil boundary and the varying sampling distances from the mountain front. The shallowest depth of pedogenic clay occurs in Holocene and post-Pinedale soils, reflecting development under a dry interglacial climate; the greater depth of clay movement in older soils reflects development under more moist glacial climates. Clay depths for soils older than post-Pinedale may be influenced by nonclimatic processes such as increased AWC with age or surface erosion of fines. As in mountain-front soils, the similarity of the depths of pedogenic clay in older soils implies that pre-Pinedale glaciations were no more moist than the

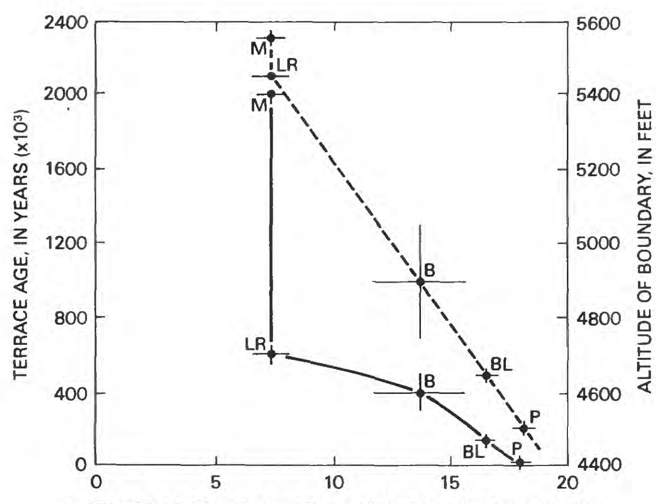

Figure 18. Terrace age (solid line) and altitude (dashed line) of calcic-noncalcic soil boundary plotted against distance of boundary from mountain front. Horizontal bars give range of position of boundary. Vertical bars on age line are estimated age ranges of terraces; vertical bars on elevation line are altitude ranges of boundary. P, Pinedale; BL, Bull Lake; B, Boyd; LR, Lower Roberts; M, Mesa.

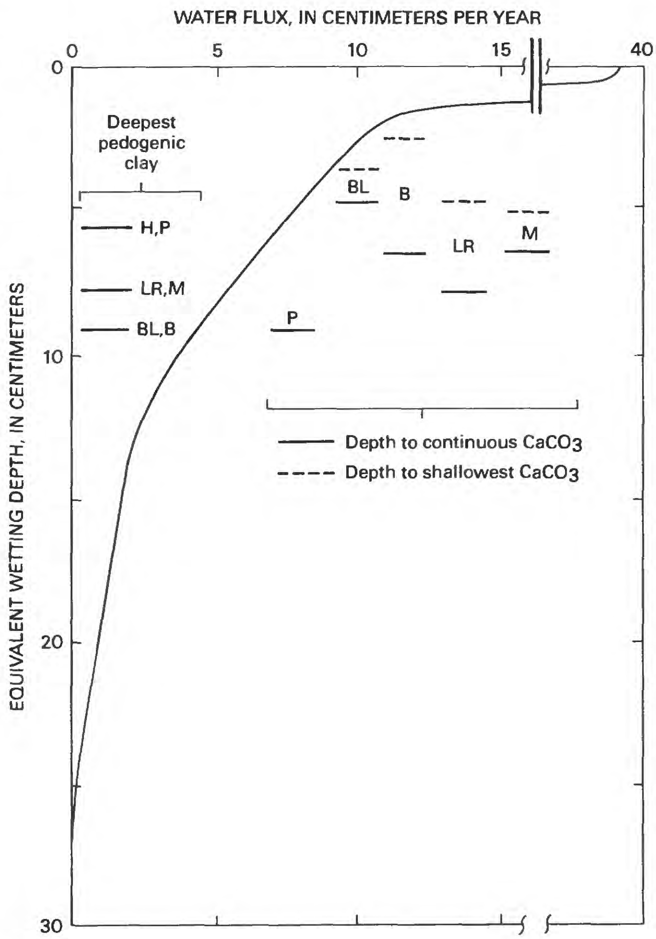

Figure 19. Water movement and pedogenic features of transition soils. Average yearly water movement (curved line) for 26-year rainfall record at Roberts using Arkley's (1963) method. Evapotranspiration estimated from temperatures at Red Lodge and Joliet. Limits of clay and $CaCO_3$ calculated by estimating available water-holding capacity for each horizon from textural data (Salter and Williams, 1967) and expressed in centimeters of wetting depth of yearly precipitation. Pedogenic clay depth defined as base of B horizon. Terraces are H, Holocene; P, Pinedale; BL, Bull Lake; B, Boyd; LR, Lower Roberts; M, Mesa.

Pinedale glaciation. Clays in the transition soils older than post-Pinedale have been formed at or translocated to somewhat shallower depths than clays in mountain-front soils of the same age (compare figs. 16 and 19). Transition soils have similar or greater amounts of textural fining when compared to mountain-front soils of the same age (figs. 10 and 14). Thus, it appears that shallower depths of clays in transition soils reflects the drier climate of this zone, rather than lesser soil development.

Basin Soils

Basin soils display field morphology that suggests continuous accumulation of $CaCO_3$. The tops of $CaCO_3$ horizons are smooth and do not vary greatly across extensive exposures. $CaCO_3$ is accumulating in clay-rich B2t and B3t horizons of soils (supplementary tables 1 and 3). This coexistence of $CaCO_3$ and clay has been interpreted to represent either (1) a change to more arid climate that permits $CaCO_3$ precipitation in horizons where clay was being formed or translocated (for example Gile and others, 1966), or (2) accumulation of $CaCO_3$ in clay-rich horizons after lower horizons have been plugged by $CaCO_3$ cementation so that soil water can no longer freely percolate. The oldest basin soils on Rock Creek are not plugged, but they may have accumulated enough clay and $CaCO_3$ to change the infiltration rate of water. However, the young post-Pinedale soils also possess calcareous argillic horizons. At least for these young soils, the B2tca and B3tca horizons probably reflect changes to an interglacial climate.

Basin soils preserve the most complete record of climatic change along Rock Creek. The climate in the basin area fluctuated enough to cause minor changes, but not enough to destroy traces of former changes. I infer that changes in moisture occurred from micromorphological relationships of $CaCO_3$ and clay revealed in petrographic thin sections of soil peds. Thin sections sections of peds from the calcareous B horizons show secondary $CaCO_3$ as masses within the soil matrix or as coatings on sand grains (fig. 20). Secondary $CaCO_3$ locally displays variation in texture and color in roughly concentric rings or sometimes in crosscutting relationships (fig. 20B and C). The areas characterized by particular textures or colors are commonly outlined by very thin yellow bands (fig. 20B and C) that go extinct upon rotation of the microscope stage; these bands resemble oriented clay argillans in noncalcareous soils. Similar features in calcareous soils have been reported by Morozova (1964), Allen and Goss (1974), Mermut and Jongerius (1980), and Dalsgaard and others (1981). That clay can be translocated through calcareous materials has been documented by Goss and others (1973) in experiments on calcareous playa sediments.

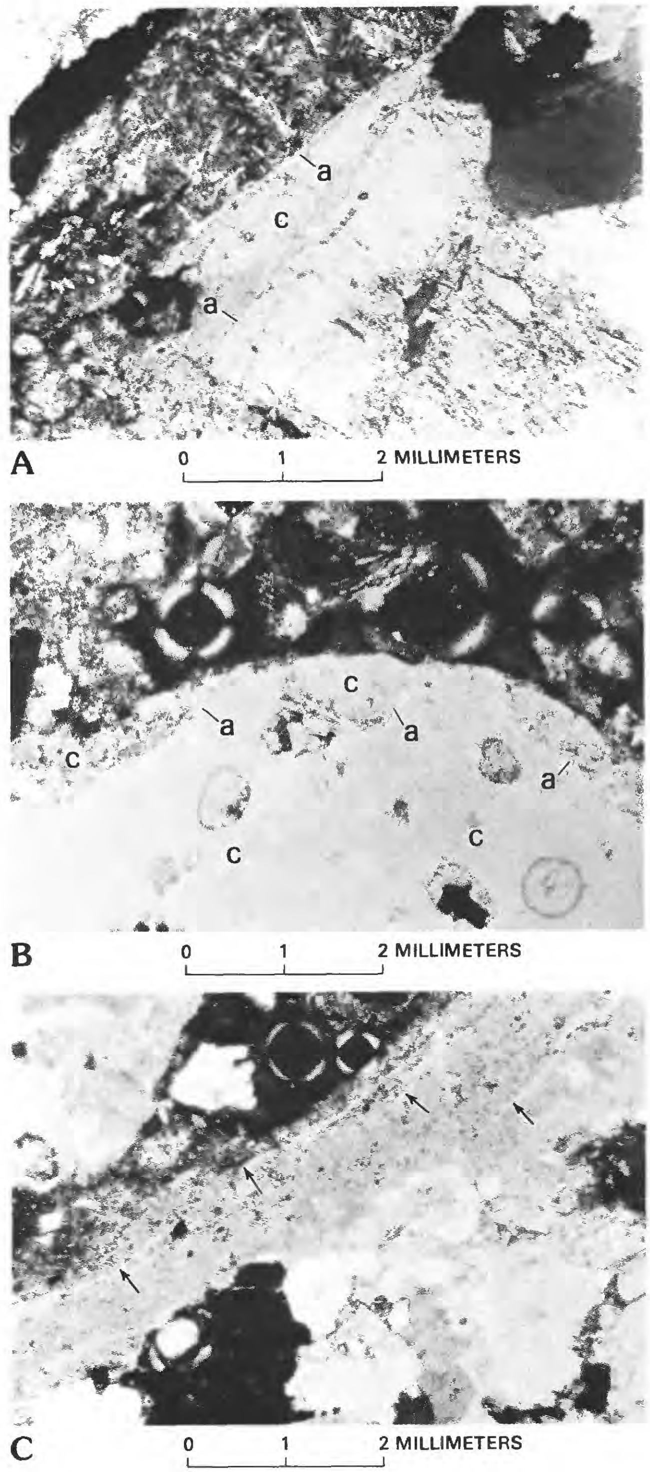

Figure 20. Photomicrographs (crossed nicols) of argillans and pedogenic $CaCO_3$ in basin soils. A, Two sand grains are separated by a wedge of $CaCO_3$ (c). Grain argillans (a) are visible along edges of both grains (best seen on lower side of upper left grain). B, Mass (c) of pedogenic $CaCO_3$ engulfs sand and silt grains; its rim has a different visual texture than the main mass. A thin white line (a) interpreted as an argillan separates the two textures of $CaCO_3$. Jagged appearance of the contact between textures may reflect dissolution of part of the main mass of $CaCO_3$ prior to accretion of a clay band and more $CaCO_3$. C, Another $CaCO_3$ mass contains two or three light streaks (arrows) representing argillans engulfed by $CaCO_3$.

The maximum number of alternating argillans and $CaCO_3$ layers forming a mass of secondary $CaCO_3$ increases with age of the soil; that relationship may reflect alternations of glacial and interglacial climates. I believe that $CaCO_3$ precipitates in the B horizons of basin soils during dry interglacials. Moister glacial climates partly dissolve accumulations of $CaCO_3$, or coat the $CaCO_3$ masses with translocated clay particles, forming argillans. The argillans are surrounded by $CaCO_3$ precipitation in the next interglacial period.

The depth to maximum accumulations of $CaCO_3$ and pedogenic clay is related to the depth of water penetration (fig. 21) (Jenny and Leonard, 1939; Arkley, 1963). The upper limits of $CaCO_3$ are not shown because in most soils $CaCO_3$ is very close to the surface.

The depth to maximum $CaCO_3$ accumulation (K horizons in pre-Bull Lake soils) increases with age of the soil, suggesting that older interglacials were progressively wetter. If successively older interglacials were wetter, then the thickness of maximum $CaCO_3$ horizons should increase as $CaCO_3$ accumulates at progressively shallower depths. However, the thickness of maximum $CaCO_3$ horizons is random with respect to age. Alternatively, the trend of increasing depth to maximum $CaCO_3$ may be age related rather than climate related, and may be caused by increasing AWC by accumulation of fines.

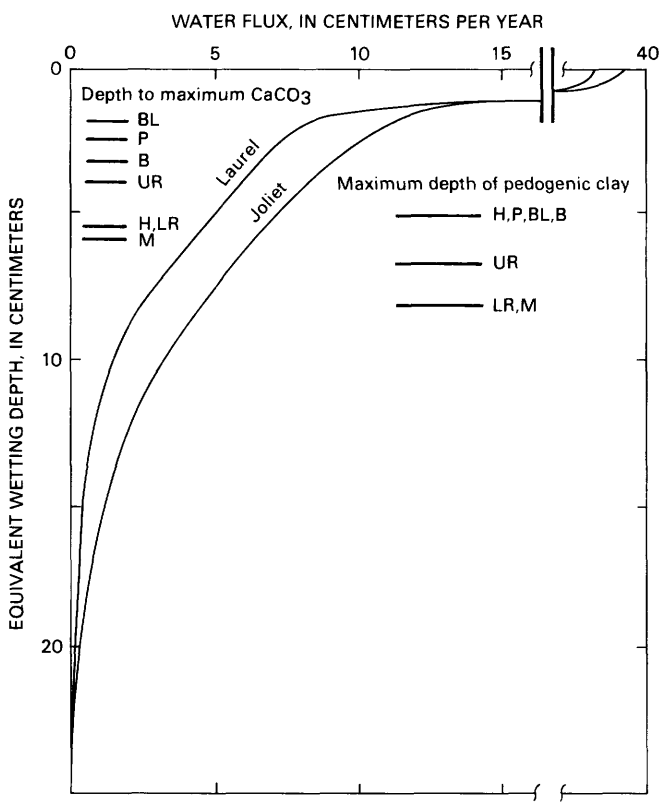

Figure 21. Water movement and pedogenic features of basin soils. Average yearly water movement (curved line) calculated for a 24-year record at Joliet and a 25-year record at Laurel (soil sites lie halfway between these two towns) using Arkley's (1963) method. Limits of clay and $CaCO_3$ calculated by estimating available water-holding capacity for each horizon from textural data (Salter and Williams, 1967) and expressed in centimeters of wetting depth of yearly precipitation. Pedogenic clay depth defined as base of B horizon. Terraces are H, Holocene; P, Pinedale; BL, Bull Lake; B, Boyd; LR, Lower Roberts; UR, Upper Roberts; M, Mesa.

The depth of pedogenic clay increases with the age of basin soils, perhaps because AWC increases with age. In general, pedogenic clays have moved about as deep in older basin soils as clays in transition soils of corresponding age. Because the rates of textural fining are similar (figs. 12 and 14), climates in the two areas may have been similar through time. Despite textural fining with age in post-Boyd to post-Pinedale soils, the soils have similar depths of pedogenic clay. As with the mountain-front and transition soils, these relations imply that pre-Pinedale glaciations were no more moist than the Pinedale glaciation.

The micromorphological evidence and the plots of color paling and color lightening and pedogenic $CaCO_3$ with time (figs. 12 and 13) indicate that while some dissolution and leaching of $CaCO_3$ has occurred in basin soils, these soils have been dominated by accumulation of $CaCO_3$. This permits evaluation of the viability of the glacial climatic model proposed for basin soils (fig. 5). In the proposed model, precipitation is held constant, but mean annual temperature is decreased by 10 ^{o}C. The reconstructed glacial surplus of water available for leaching at Laurel and Joliet is 12-14 cm/yr, similar to the modern water surplus at Red Lodge, where no soils are calcareous. If the reconstruction is correct, such moisture conditions should have caused substantial dissolution of $CaCO_3$ in basin soils. In order to prevent removal of much $CaCO_3$, the net yearly amount of moisture available to wet the soil should roughly equal the soil AWC. Most soils on Rock Creek terraces have in excess of 10 cm AWC. If the glacial water surplus was zero, with just enough moisture available to wet the soil, but not leach it of soluble material, actual precipitation would have had to decrease by about 50 to 60 percent. Gates (1976) modeled a 35 percent decrease of precipitable moisture in the northern hemisphere at 18 ka.

Summary of Climatic Inferences

The transition and basin soils show evidence of periodic dissolution of $CaCO_3$ that is consistent with periodically greater effective glacial soil moisture reconstructed by assuming a 10 ^{o}C decrease in mean annual temperature. This model must be modified by a decrease in mean annual precipitation on the order of 50 to 60 percent in order to preserve most of the $CaCO_3$ in the basin soils. The decrease in precipitation may have been regional in extent, but no reinforcing evidence can be derived from mountain or transition soils.

The depths of pedogenic clay indicate that glacial climate in all three chronosequences during the Pinedale glaciation was about as wet as previous glaciations. The decreasing depth of clays in a downstream direction for soils on any given terrace suggest that climate has been consistently drier away from the mountain front.

The climate of interglacials is inferred from positions of pedogenic $CaCO_3$ in basin soils, and from the changing position of the calcic-noncalcic soil boundary. Data from the calcareous horizons of basin soils are ambiguous. The increasing depth to maximum pedogenic $CaCO_3$ may indicate that older interglacials were more moist. But thicknesses of the maximum $CaCO_3$ horizons do not increase with soil age, and this argues against such a trend in interglacial climates. If Richmond's (1972) model is correct, the calcic-noncalcic soil boundaries suggest that interglacials have become progressively wetter since 600,000 years ago. However, the approach of the boundary to the mountain front with time could reflect normal soil processes rather than changes in interglacial climate.

Glacial-interglacial climatic changes are represented in outcrop by wavy, irregular upper boundaries of calcareous horizons in transition soils (an interglacial to glacial change), and by precipitation of $CaCO_3$ in the B horizons of basin soils (a glacial to interglacial change). Micromorphological relationships between pedogenic $CaCO_3$ and oriented clay bands in basin soils appear to preserve evidence of multiple climatic oscillations.

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FIELD METHODS AND CALCULATIONS

Sampling and Description

Soils studied along Rock Creek were sampled in hand-dug holes or backhoe pits at sites that had minimal amounts of postdepositional erosion or burial. These sites were supplemented by exposures in gravel pits, irrigation ditches, and roadcuts (supplementary table 1, part 1, and fig. 2). Replicate soils on terraces in a given climatic zone were sampled locally in order to assess soil variability.

Sites were selected to minimize differences in present relief. Initial depositional relief probably influenced soil development, but it is impossible to assess this effect without extensive replicate sampling. All sites are located on the best preserved north- or east-sloping terrace surfaces available. The soils sampled in commercial gravel pits have relatively thin A and B horizons because the pits are usually located on the edges rather than in the centers of terraces (fig. 2). The Upper Roberts terrace remnants are not well preserved, and near-surface calcic horizons may reflect soil erosion from these remnants. This is especially noticeable in the basin chronosequence, where post-Upper Roberts soils RC-44 and RC-25 are calcareous at the surface. The Mesa terrace has been exposed to weathering for 2 million years, so it is not surprising that some soils on this surface (RC-28, RC-8, and RC-26B) show signs of erosion (such as thin or abnormally clay-poor horizons).

Horizon nomenclature and soil property descriptions (supplementary table 1, part 2) follow Soil Survey Staff (1975) usage, with the following three exceptions. (1) Texture modifiers were added to describe gravel content. (2) The letter "K" designates a horizon dominated by pedogenic $CaCO_3$ (Gile and others, 1965). $CaCO_3$ stages follow those proposed by Bachman and Machette (1977). (3) Field textural descriptions for Rock Creek soils were corrected using laboratory-determined carbonate-free particle-size data. Moist and dry colors were obtained with a Munsell soil color chart. pH was determined in the laboratory with a pH meter.

Index of Soil Development

Soil field data, which is measured mainly on ordinal scales, were converted to ratio data using Harden's (1982a) index of soil development, in which a point system is used to quantify various field properties of soils. Points for each horizon are then normalized to give all properties equal scales and multiplied by the horizon thickness; the products are summed for each soil. Thus, individual properties can be examined with depth in one soil or compared between soils, or several properties can be combined to obtain a profile-development index value for each soil.

Two modifications were made to Harden's index. (1) Color paling and color lightening in the index are two separate color properties that assess the increase of $CaCO_3$ in a soil (Harden and Taylor, 1983). Because the two properties reflect the same phenomenon, they were combined in the present study into one property. (2) The change of pH in the index is assessed in terms of pH lowering, and this works well in relatively moist environments, such as the mountain-front climate at Red Lodge. In the transition and basin chronosequences, however, pH can either decrease or increase (supplementary table 1, part 2) depending upon depth in the soil profile. Values of pH in the latter chronosequences generally decrease from the parent material state in A and B horizons, but increase in the calcareous K and C horizons. Change in pH for the transition and basin chronosequences was therefore quantified as the increase of pH from the parent material state. Parent material pH was determined from modern river deposits and relatively unaltered Holocene-aged C horizons, and increases along the transect from 6.8 at the mountain front, to 7.4 in the transition zone, to 8.0 in the basin. 1.5 was used as the normalization value for pH increase, because that was the maximum value of pH change observed in these soils; 3.5 was used to normalize pH decrease (calculation method in Harden, 1982a).

Dust Traps

A dust trap was set out near Joliet (fig. 2) to assess aerosolic additions to the soils. A plastic-lined aluminum tray, 29.5 x 29.5 x 6.5 cm in size, was filled with marbles and mounted on a pole about 2 m above the ground (Gile and Grossman, 1979). After one year the trap was removed and the dust collected by washing the trap and marbles with distilled water. Upon collection it was learned that the trap on Rock Creek may have received greater than normal atmospheric fallout because a nearby field had been plowed. This problem exemplifies the more general problem of increased regional dust fallout due to human activities. Nevertheless, dust trap data seems better than no data at all, and may at least suggest trends in eolian influence on soil development over long time periods.

Micromorphology

Oriented soil peds were collected from horizons of many soils. These were later impregnated with blue epoxy and thin-sectioned in order to investigate the micromorphological relationships of various soil components. Of special interest in Rock Creek soils was the relation of pedogenic $CaCO_3$ and translocated clay particles.

Water Movement

Arkley's (1963) method of calculating water movement in soils is used to examine the relationship between local climate and the depth of clay or $CaCO_3$ accumulation. Month-by-month precipitation data for the climate records at several towns, and average monthly potential evapotranspiration (using van Hylckama's method, 1959), are used to calculate monthly excesses of precipitation over evaporation—that is, the depth of water available to wet the soil in a given month. The average amount of water per year that passes any given depth in a soil can then be calculated. If the available water-holding capacity (AWC) of the various horizons is known or can be estimated, the amount of water can be plotted against actual soil depth. AWC is usually measured in the laboratory, but for this study it was estimated from field textural data using Salter and Williams's (1967) method. They state that their method has a mean error for estimated vs. measured AWC values of ±10 percent using a 10 textural-class (laboratory) system.

SUPPLEMENTARY TABLES

Supplementary table 1, part 1. Sample locations and site conditions

[Percentage of bare ground (in parentheses) is strongly influenced by cultivation and grazing practices. Parent material textures: gr/S = gravel and sand, SL = sandy loam, L = loam]

Site	Named terrace deposit	Elevation (ft)	Modern vegetation	Modern land use	Type of excavation	Parent material texture	Location (Montana Base Meridian)
			Mountain-front chronosequence				
RC-38	Holocene	5,700	mixed aspen and meadow (0)	grazing	backhoe	SL,gr/S	SW/4,NW/4,NW/4, Sec. 3, T. 8 S., R. 20 E.
RC-21	Pinedale	5,780	meadow, nearby forest (0)	residen-tial	backhoe	SL,gr/S	NE/4,SW/4,NE/4, Sec. 4, T. 8 S., R. 20 E.
RC-15	Pinedale	5,625	mixed conifer/ aspen,meadow(0)	residen-tial	roadcut	SL,gr/S	SW4/,SW/4,NE/4, Sec. 34, T. 7 S., R. 20 E.
RC-31	Bull Lake	6,010	meadow, sagebrush (5)	grazing	backhoe	SL,gr/S	SW/4,NW/4,NE/4, Sec. 9, T. 8 S., R. 20 E.
RC-17	Bull Lake	5,670	meadow, alder (5)	grazing	irrigation ditch	SL,gr/S	SW/4,NW/4,NW/4, Sec. 27, T. 7 S., R. 20 E
RC-30	Boyd (?)	6,010	meadow, sagebrush (5)	grazing	backhoe	SL,gr/S	NW/4,NE/4,NE/4, Sec. 9, T. 8 S., R. 20 E.
RC-29	Lower(?) Roberts	6,060	meadow, sagebrush (5)	grazing	gravel pit	SL,gr/S	SE/4,SE/4,NE/4, Sec. 9, T. 8 S., R. 20 E.
RC-16	Lower(?) Roberts	5,510	meadow, sagebrush, (5)	cultiva-tion	gravel pit	SL,gr/S	SE/4,NE/4,SW/4, Sec. 14, 14, T. 7 S., R. 20 E.
RC-28	Mesa	6,050	meadow, sagebrush (5)	grazing	backhoe	SL,gr/S	NW/4,NW/4,SE/4, Sec. 3, T. 8 S., R. 20 E.
RC-14	Mesa	5,865	meadow, alder, sagebrush (5)	grazing, hay	irrigation ditch	SL,gr/S	SW/4,SE/4,SW/4, Sec. 26, T. 7 S., R. 20 E.
			Transition chronosequence				
RC-40	Holocene	4,520	meadow, riparian vegetation (0)	grazing	stream cut	SL,gr/S	NW/4,NW/4,NE/4, Sec. 32, T. 5 S., R. 21 E.
RC-42	Holocene	4,305	grasses (0)	grazing, hay	backhoe	SL,gr/S	NW4/,NE/4,NE/4, Sec. 16, T. 5 S., R. 21 E.
RC-22	Pinedale	4,465	grasses, thistles (5)	grazing	streamcut	SL,gr/S	NW4/,SW/4,NW/4, Sec. 28, T. 5 S., R. 21 E.
RC-12	Bull Lake	4,820	grasses, alder, sagebrush (5)	grazing, hay	gravel pit	SL,gr/S	SW/4,NE/4,NE/4, Sec. 12, T. 6 S., R. 20 E.
RC-32	Bull Lake	4,525	grasses (0)	grazing, hay	roadcut	SL,gr/S	NE/4,NE/4,NE/4, Sec. 30, T. 5 S., R. 21 E.
RC-41	Bull Lake	4,420	grasses (5)	grazing, hay	hand-dug hole	SL,gr/S	SE/4,SW/4,SE/4, Sec. 17, T. 5 S., R. 21 E.
RC-11	Boyd	4,525	grasses, sagebrush (10)	grazing, hay	gravel pit	SL,gr/S	NE/4,SW/4,NW/4, Sec. 28, T. 5 S., R. 21 E.
RC-37	Boyd	4,425	grasses, sagebrush (10)	grazing, hay	gravel pit	SL,gr/S	SE/4,SE/4,SE/4, Sec. 16, T. 5 S., R. 21 E.
RC-34	Lower Roberts	5,115	grasses, sagebrush (10)	grazing, hay	backhoe	SL,gr/S	SE/4,NW/4,SW/4, Sec. 30, T. 6 S., R. 21 E.
RC-35	Lower Roberts	4,265	grasses, cactus, sagebrush (20)	grazing	backhoe	SL,gr/S	NW/4,SE/4,NE/4, Sec. 36, T. 4 S., R. 21 E.
RC-6	Upper(?) Roberts	4,480	grasses, sagebrush (10)	cultiva-tion	gravel pit	SL,gr/S	SW/4,SW/4,NE/4, Sec. 15, T. 5 S., R. 21 E.
RC-36	Upper Roberts	4,320	grasses, cactus, sagebrush (20)	grazing	backhoe	SL,gr/S	NE/4,SE/4,SW/4, Sec. 36, T. 4 S., R. 21 E.
RC-33	Mesa	5,245	grasses, sagebrush (10)	grazing	backhoe	SL,gr/S	NW/4,SE/4,NW/4, Sec. 33, T. 6 S., R. 21 E.
RC-8	Mesa	5,145	grasses, sagebrush (10)	grazing	gravel pit	SL,gr/S	SW/4,NW/4,SW/4, Sec. 27, T. 6 S., R. 21 E.

Supplementary table 1, part 1. Sample locations and site conditions--Continued

Site	Named terrace deposit	Elevation (ft)	Modern vegetation	Modern land use	Type of excavation	Parent material texture	Location (Montana Base Meridian)
			Basin chronosequence				
RC-46A	Holocene	3,387	grasses (5)	grazing, residential	backhoe	L,gr/S	SE/4,NE/4,SW/4, Sec. 25, T. 3 S., R. 23 E.
RC-46B	Holocene	3,387	grasses (5)	grazing, residential	backhoe	L,gr/S	SE/4,NE/4,SW/4, Sec. 25, T. 3 S., R. 23 E.
RC-20	Pinedale	3,480	grasses, edge of cornfield (5)	cultivation	gravel pit	SL,gr/S	SE/4,SE/4,SW/4, Sec. 11, T. 4 S., R. 23 E.
RC-43	Pinedale	3,430	grasses, edge of wheatfield (5)	cultivation	gravel pit	L,gr/S	SW/4,NE/4,SW/4, Sec. 36, T. 3 S., R. 23 E.
RC-27	Bull Lake	3,465	grasses, sagebrush (5)	cultivation	backhoe	SL,gr/S	SE/4,SW/4,NE/4, Sec. 23, T. 3 S., R. 23 E.
RC-23	Boyd	3,620	grasses, sagebrush (20)	grazing	backhoe	SL,gr/S	SE/4,NE/4,SE/4, Sec. 34, T. 3 S., R. 23 E.
RC-24	Lower Roberts	3,700	grasses, sagebrush (20)	grazing	backhoe	SL,gr/S	NE/4,SW/4,NE/4, Sec. 34, T. 3 S., R. 23 E.
RC-25	Upper Roberts	3,810	grasses, sagebrush (20)	grazing	hand-dug hole	SL,gr/S	SW/4,SW/4,SW/4, Sec. 27, T. 3 S., R. 23 E.
RC-44	Upper Roberts	3,850	grasses, sagebrush (20)	grazing	hand-dug hole	SL,gr/S	SE/4,SW/4,SE/4, Sec. 28, T. 3 S., R. 23 E.
RC-26A	Mesa	4,495	grasses, sagebrush, pines(10)	grazing	backhoe	SL,gr/S	SW/4,SW/4,SE/4, Sec. 12, T. 5 S., R. 22 E.
RC-26B	Mesa	4,490	grasses, sagebrush, pines(10)	grazing	backhoe	SL,gr/S	NE/4,SW/4,SE/4, Sec. 12, T. 5 S., R. 22 E.

Supplementary table 1, part 2. Field descriptions

[Analyst: M. C. Reheis, U.S. Geological Survey. --, not measured]

Surface and age, ka	Sample	Horizon	Depth (cm)	Lower boundary	Moist color	Dry color	Texture	Structure	Wet consistence	Clay films	pH	Assumed parent material (<2 mm) Texture	Assumed parent material (<2 mm) Wet consistence	Stage $CaCO_3$
						Mountain-front chronosequence								
Holocene 7	RC-38	A1	0-9	c,s	10YR2/1	2.5Y4/2	sgLS	1gr	so,po	0	6.3	LS	so,po	0
		2A31	9-22	g,s	10YR2/2	10YR4/2	sgLS	2gr,1fsbk	so,po	0	6.1	LS	so,po	0
		2A32	22-33	g,w	10YR2/2.5	10YR4.5/2.5	gLS-	2gr,1fsbk	so,po	0	6.0	S	so,po	0
		2AC	33-46	g,w	10YR3/3	10YR5/3	gS	sg,1fsbk	so,po	0	6.0	S	so,po	0
		$3C_1ox$	46-85	g,w	10YR5/4	2.5Y6/2.5	vgLS-	m	so,po	0	6.3	LS-	so,po	0
		$3C_2ox$	85-120+	--	10YR5/3	10YR6.5/3	vgLS-	m	so,po	0	5.9	LS-	so,po	0
Pinedale 20	RC-21	A	0-5	g,s	7.5YR2/2	7.5YR4/3	sgSL	1gr	so,po	0	6.1	SL	so,po	0
		B1t	5-12	g,s	7.5YR3/3	7.5YR4.5/4	gSL+	1fsbk	ss,ps	1npf	6.3	SL	so,po	0
		B2t	12-25	g,s	7.5YR3/4	7.5YR4.5/4	gL	1msbk	ss,ps	1npf	6.3	SL	so,po	0
		2B3t	25-38	g,w	7.5YR4/6	7.5YR5/5	vgSL	1msbk	ss,po	0	6.4	LS	so,po	0
		$3C_1ox$	38-73	g,s	10YR4/4	10YR6/5	vgS	m	so,po	0	6.6	S	so,po	0
		$3C_2ox$	73-110+	--	10YR5/4	10YR7/4	vgS	m	so,po	0	6.8	S	so,po	0
	RC-15	A	0-8	g,s	7.5YR2/2	10YR2/3	sgSL	1gr	so,po	0	6.0	SL	so,po	0
		2B2t	8-23	g,s	7.5YR2/3	7.5YR4/3	vgSL-	1fsbk	so,po	1nco	5.9	S	so,po	0
		2B3	23-43	d	7.5YR3/5	7.5YR4/4	vgLS-	sg,m	so,po	0	5.8	S	so,po	0
		2Cox	43-68+	--	7.5YR4/4	7.5YR5/5	vgS	m	so,po	0	6.0	S	so,po	0
Bull Lake 120	RC-31	A1	0-8	c,s	7.5YR2/1	7.5YR 3.5/2.5	sgSL	2gr	so,po	0	6.5	LS	so,po	0
		A3	8-19	g,s	7.5YR2/1.5	7.5YR 3.5/2.5	sgSL	2gr, 2fsbk	ss,ps	0	6.0	LS	so,po	0
		B1t	19-32	d	7.5YR4/4	8.75YR5/4	gSL+	2m-csbk	s,p	2npf	6.1	LS	so,po	0
		B21t	32-54	c,s	7.5YR4.5/6	8.75YR6/5	gSL	2m-csbk	s,p	2npf	6.2	LS	so,po	0
		B22t	54-81	c,s	5YR4/8	5YR5/7	gSCL+	3csbk	s,p	2npf	6.3	LS	so,po	0
		2B31t	81-123	d	10YR5/6	10YR6/5	vgLS	2f-msbk	ss,po	2nco	6.6	S	so,po	0
		2B32t	123-145	d	10YR4/6	10YR5.5/6	vgLS	sg,m	so,po	1nco	6.8	S	so,po	0
		2Cox	145-200+	--	10YR5/5	10YR6/5	vgS	m	so,po	0	6.8	S	so,po	0
	RC-17	A	0-9	g,s	7.5YR2/2	7.5YR4/3	sgL	2fsbk	so,ps	0	6.4	SL	so,po	0
		B1t	9-20	g,s	7.5YR2/4	7.5YR4.5/4	sgSCL-	1fsbk, 1gr	so,ps	0	6.1	SL	so,po	0
		B2t	20-31	g,s	7.5YR4/4	7.5YR5/5	gSCL-	2msbk	s,p	2npf	5.8	LS	so,po	0
		B31t	31-50	g,s	7.5YR4/5	7.5YR5/6	gSL+	2csbk	s,p	2npf	5.4	LS	so,po	0
		2B32t	50-122	d	7.5YR4/8	7.5YR5.5/8	vgLS	2csbk,sg	so,po	1nco	5.7	S	so,po	0
		2Cox	122-136+	--	10YR4/5	10YR6/4	vgS	m	so,po	0	5.1	S	so,po	0
Boyd 415	RC-30	A1	0-9	g,s	10YR2/2	10YR3/2	sgSL	2gr	so,po	0	6.2	SL	so,po	0
		A3	9-17	c,s	10YR2/1	10YR3/2	sgSL	2gr,2fsbk	so,po	0	6.1	SL	so,po	0
		B1t	17-29	g,s	7.5YR3.5/4	8.75YR4/5	gSL	1f-msbk	s,ps	2npf	6.1	LS	so,po	0
		B2t	29-53	g,s	7.5YR4/6	7.5YR4.5/6	gSL	3csbk	s,p	3npf	6.2	LS	so,po	0
		2B31t	53-81	d	7.5YR4.5/6	7.5YR5/5	vgSL	3msbk	ss,ps	3nco	6.4	S	so,po	0
		2B32t	81-170	d	8.75YR5/5	8.75YR6/7	vgLS+	sg,m	so,po	1nco	6.7	S	so,po	0
		2Cox	170-250+	--	10YR5/5	10YR6/6	vgS	m	so,po	0	6.7	S	so,po	0
Lower (?) Roberts 600	RC-29	A1	0-9	c,s	7.5YR2/1.5	7.5YR4/3	sgSL	2gr	so,po	0	6.2	LS	so,po	0
		A3	9-18	g,s	7.5YR2/2	7.5YR4/2.5	gSL	2gr,1msbk	so,po	2npf	5.9	LS	so,po	0
		B1t	18-30	g,s	7.5YR3/3	8.75YR4/3	gSL	2msbk	so,po	3npf	5.9	LS	so,po	0
		B2t	30-50	g,s	7.5YR4/4	8.75YR5/5	gSL	2m-csbk	s,ps	3npf	6.0	LS	so,po	0
		2B31t	50-79	g,s	7.5YR3/3	8.75YR4/3	vgSL	2msbk	s,ps	3npf	5.9	LS	so,po	0
		3B32t	79-167	d	10YR4/4	10YR6/5	vgLS	sg,m	so,po	2nco	6.7	S	so,po	0
		3Cox	167-260+	--	10YR5/4	10YR6/5	vgLS	m	so,po	0	6.9	S	so,po	0
	RC-16	A	0-27	g,s	10YR2/3	10YR3/3	sgSL	2gr	ss,po	0	5.4	SL	so,po	0
		B1t	27-47	g,s	7.5YR3/4	7.5YR4/4	gSL	3fsbk	s,ps	2npf	5.6	LS	so,po	0
		2B2t	47-72	g,s	7.5YR4/8	7.5YR4/8	vgSL+	3msbk	s,ps	3mkpf	5.6	LS	so,po	0
		2B3t	72-127	g,s	7.5YR4/6	7.5YR4/7	vgSL+	sg,m	ss,po	2nco	5.9	LS	so,po	0
		2Cox	127-197+	--	10YR5/5	10YR5/6	vgLS	m	so,po	0	5.7	LS	so,po	0
Mesa 2,000	RC-28	A	0-7	c,s	7.5YR2/2	7.5YR4/2.5	sgSL	1gr	so,po	0	6.0	LS	so,po	0
		B1t	7-11	c,s	8.75YR2/2	8.75YR4/3	gSL-	2msbk	so,po	1npf	6.0	LS	so,po	0
		B2t	11-17	c,s	7.5YR3/4	8.75YR4/4	gSL	2msbk	so,ps	2npf	6.0	LS	so,po	0
		2B31t	17-47	g,s	7.5YR4/4	7.5YR4.5/5	vgSL-	1fsbk	so,po	1npf	6.0	S	so,po	0
		2B32t	47-141	d	7.5YR4.5/5	7.5YR5.5/6	vgLS	sg,m	so,po	1nco	6.6	S	so,po	0
		2Cox	141-270+	--	10YR5/5	10YR5.5/6	vgS	m	so,po	0	7.1	S	so,po	0
	RC-14	A	0-17	g,s	7.5YR2/2	7.5YR3/3	sgSL+	2gr	ss,ps	0	5.3	SL	so,po	0
		B1t	17-32	g,s	7.5YR3/4	7.5YR4.5/4	sgSCL-	2msbk	s,p	3mkpf	5.6	SL	so,po	0
		B2t	32-44	g,s	5YR4/5	7.5YR5/5	sgSCL-	3msbk	vs,vp	3mkpf	5.6	SL	so,po	0
		2B31t	44-84	g,s	7.5YR4.5/6	7.5YR5/6	gSL	1fsbk	ss,ps	2npf	5.6	LS	so,po	0
		3B32t	84-144	d	7.5YR4.5/6	7.5YR5/6	vgLS+	sg,m	so,po	2nco	6.2	LS	so,po	0
		3Cox	144-164+	--	10YR4/6	10YR5.5/6	vgS	m	so,po	0	6.3	S	so,po	0

Supplementary table 1, part 2. Field descriptions--Continued

Surface and age, ka	Sample	Horizon	Depth (cm)	Lower boundary	Moist color	Dry color	Texture	Structure	Wet consis- tence	Clay films	pH	Assumed parent material (<2 mm) Texture	Assumed parent material (<2 mm) Wet con- sistence	Stage $CaCO_3$
							Transition chronosequence							
Holocene 7	RC-40	A	0-13	c,s	10YR2/2	2.5Y4/2	gfSL	1gr,1msbk	so,po-	0	7.1	SL	so,po	0
		3s	13-46	g,w	10YR2/2.5	10YR4/3	gfSL	2csbk	so,po	0	6.6	SL	so,po	0
		2C$_1$ox	46-75	g	10YR4/4	10YR5/4	vgS	m	so,po	0	6.8	S	so,po	0
		2C$_2$ox	75-310	va	10YR5/3	10YR6/3	vgS	m	so,po	0	7.0	S	so,po	0
		R	310+	--	--	--	--	--	--	--	--	--	--	--
	RC-42	A1	0-6	g	10YR2.5/2	10YR4/3	gSL	1gr	so,po	0	7.1	SL	so,po	0
		A3	6-37	g	10YR2/2	10YR4/2	vgSL	1fsbk	so,po	0	6.1	SL	so,po	0
		2Bs	37-55	a,w	10YR3/3	10YR4.5/3	sgSL	1msbk	so,po	0	6.7	SL	so,po	0
		3Bb	55-73	c,s	10YR2/3	10YR4/3	vgSL	1fsbk	so,po	0	6.8	LS	so,po	0
		3Coxb	73-200+	--	10YR4/4	10YR5/4	vgS	m	so,po	0	7.0	S	so,po	0
Pinedale 20	RC-22	A	0-5	g,s	10YR3/2	10YR5/3	sgL	2gr	so,po	0	6.9	SL	so,po	0
		B1t	5-25	g,s	10YR2/3	10YR4/2.5	sgSL	1fsbk	ss,ps	0	6.6	SL	so,po	0
		B2t	25-43	g,s	7.5YR3/2	7.5YR4/3	gSL+	2msbk	s,ps	1npf	6.8	LS	so,po	0
		2B3t	43-57	g,s	10YR3/2	10YR4/2.5	vgSL-	sg	so,po	0	6.9	LS	so,po	0
		2C$_1$ox	57-78	g,s	10YR3/3	10YR5/3	vgLS	m	so,po	0	7.1	LS	so,po	0
		2C$_2$ox	78-175	a,s	10YR5/4	10YR6/4	vgLS	m	so,po	0	6.9	LS	so,po	0
		3Cca	175-197	c,s	2.5Y5/3	2.5Y6/3	vgS	m	so,po	0	7.9	S	so,po	I
		3Cn	197-240+	--	2.5Y5/3	2.5Y7/3	vgS	m	so,po	0	7.7	S	so,po	0
Bull Lake 120	RC-12	A	0-9	g,s	10YR2/3	10YR4/4	vsgL	2gr	so,po	0	6.2	SL	so,po	0
		B1t	9-17	g,s	7.5YR4/4	7.5YR5.5/5	sgCL-	2gr,1fsbk	s,p	1npf	6.4	SL	so,po	0
		B2t	17-39	g,s	7.5YR4/7	7.5YR4/8	gSCL	1fsbk	s,p	1npf	6.4	SL	so,po	0
		2B3t	39-62	d	7.5YR4/6	7.5YR4.5/6	vgSL+	1fsbk	ss,po	1nco	6.8	S	so,po	0
		2Cox	62-122+	--	7.5YR5/6	7.5YR5/6	vgS	m	so,po	0	7.0	S	so,po	0
	RC-32	Ap	0-21	a,s	10YR5/3	10YR5/3	sgC	2fabk	vs,vp	--	7.2	SL	ss,ps	0
		2B2tca	21-37	g,s	10YR3/2.5	10YR3/1.5	gSCL	1msbk	s,p	--	7.5	LS	so,po	I
		2B3tca	37-70	g,s	10YR4/4	10YR5/4	gSL+	2msbk	s,p	--	8.0	LS	so,po	II
		3Cca	70+	--	10YR5/4	10YR6/4	vgLS-	m	so,po	--	8.1	S	so,po	I
	RC-41	A	0-8	g,s	10YR3/2	10YR5/3	sgfSL	2gr	so,po	0	6.7	SL	so,po	0
		B1t	8-17	c,s	10YR3/2	10YR5.5/2.5	gL	2msbk	s,p	1npf	6.6	LS	so,po	0
		B2t	17-28	g,w	8.5YR4/6	8.5YR4/4	gSCL+	2csbk	s,p	2npf	6.5	LS	so,po	0
		2B31t	28-51	d	10YR3.5/4	10YR4/4	vgSL-	2msbk	s,ps	2nco	6.7	S	so,po	0
		2B32t	51-65	d	10YR4/4	10YR5/4	vgSL	1f-msbk	ss,po	1nco	7.1	S	so,po	0
		2Cox	65-100+	--	10YR5/4	10YR6/6	vgS	m	so,po	0	7.3	S	so,po	0
Boyd 415	RC-11	A	0-9	g,s	7.5YR3/3	10YR3/4	gSL	2gr	so,po	0	5.6	LS	so,po	0
		B2t	9-20	g,s	7.5YR3/6	7.5YR3/6	vgSCL	2msbk	s,p	1npf	5.7	LS	so,po	0
		B3t	20-50	a,i	7.5YR4/4	7.5YR4/5	vgSL+	1msbk	s,ps	2nco	6.4	LS	so,po	0
		2C$_1$ca	50-100	d	10YR7/3	10YR7/3	vgLS	m	so,po	0	7.5	S	so,po	II+
		2C$_2$ca	100-180+	--	10YR6/3	10YR6/3	vgS	m	so,po	0	7.7	S	so,po	I
	RC-37	A	0-6	c,s	10YR2.5/2	10YR4/2.5	vsgSL	2gr	so,po	0	7.0	SL	so,po	0
		B1t	6-18	g,s	10YR3/2.5	10YR4/2.5	sgL	2msbk	s,p	1npf	7.1	SL	so,po	0
		B2tca	18-45	a,i	10YR3.5/3	10YR4/3	sgSCL-	2m-csbk, 1mpr	s,p	2npf	7.3	SL	so,po	I
		B3tca/K	45-63	g,s	10YR7/3	10YR8/1	sgSCL	1fsbk, 1mpl	ss,p	0	7.7	LS	so,po	II/ III-
		2C$_1$ca	63-109	d	10YR5.5/3	10YR7/3	vgSL+	m	ss,ps	0	7.8	LS	so,po	II+
		3C$_2$ca	109-230	d	2.5Y6/2	2.5Y7/3	vgS	m	so,po	0	8.1	S	so,po	II-
		3C$_3$ca	230+	--	--	--	vgS	m	so,po	0	--	S	so,po	I
Lower Roberts 600	RC-34	A1	0-8	g,s	10YR3/2	10YR4/2.5	sgSL+	2gr,1fpl	so,po	0	5.7	SL	so,po	0
		A3	8-14	g,s	10YR 2.5/1.5	10YR4/2.5	sgSL+	2gr, 2msbk	ss,ps	0	5.4	SL	so,po	0
		B1t	14-22	c,s	10YR2/2	10YR4/2.5	sgSL+	2msbk	s,p	1npf	5.5	SL	so,po	0
		B2t	22-37	g,i	7.5YR4/3	8.75YR5/4	sgL	3m-csbk	vs,p	2npf	5.5	SL	so,po	0
		2B3t/ca	37-54	g,i	10YR3/3.5	10YR4/3	gSL	1fsbk	so,po	0	6.1/7.6	LS	so,po	0/I-
		3Cox/ca	54-89	g,s	10YR4/3/ 10YR6/2.5	10YR5/3/ 10YR7/2.5	vgLS	m	so,po	0	6.7	S	so,po	0/II+
		3C$_1$ca	89-160	d	2.5Y5/2.5	2.5Y7/2.5	vgS	m	so,po	0	7.9	S	so,po	II
		3C$_2$ca	160-210+	--	2.5Y5/2.5	2.5Y7/2.5	vgS	m	so,po	0	7.8	S	so,po	I
	RC-35	A	0-5	c,s	10YR3/2	10YR4/2.5	sgfSL	2gr	so,ps	0	6.9	SL	so,po	0
		B1t	5-10	c,s	10YR3/2	10YR4/3	sgSCL-	2msbk	ss,ps	2npf	6.5	SL	so,po	0
		B2tca	10-18	c,s	10YR3/3	10YR4/2.5	sgSCL	2m-csbk	s,p	2mkpf	7.0	LS	so,po	I
		B3tca	18-32	g,s	10YR5/4	10YR6/3	gSL-	1f-msbk	so,ps	1npf	7.5	LS	so,po	II
		2C$_1$ca	32-54	g,s	10YR6/3	10YR8/2.5	vgLS	m	so,po	0	7.6	S	so,po	II+
		2C$_2$ca	54-135	d	10YR6/3.5	10YR7/2.5	vgLS	m	so,po	0	7.9	S	so,po	II+
		2C$_3$ca	135-225	d	10YR5.5/4	10YR7/3.5	vgS	m	so,po	0	8.0	S	so,po	II
		2C$_4$ca	225+	--	10YR5/5	10YR7/3.5	vgS	m	so,po	0	8.0	S	so,po	I

Supplementary table 1, part 2. Field descriptions--Continued

Surface and age, ka	Sample number	Horizon	Depth (cm)	Lower boundary	Moist color	Dry color	Texture	Structure	Wet consis- tence	Clay films	pH	Assumed parent material (<2 mm) Texture	Wet con- sistence	Stage $CaCO_3$
Upper(?)	RC-6	A	0-13	c,w	10YR3/2	10YR3/4	vsgSL+	1gr	ss,ps	0	6.6	SL	so,po	0
Roberts		B1t	13-30	g,s	10YR3/6	10YR4/6	sgSCL-	2msbk	s,p	2npf	6.6	SL	so,po	0
945		B2t	30-46	a,s	10YR4/4	10YR4/5	sgSCL	3msbk, 1mpr	s,p	3mkpf	6.8	SL	so,po	0
		2C$_1$ca	46-96	d	10YR7/3	10YR7/2	vgLS	m	so,po	0	7.5	S	so,po	III
		2C$_2$ca	96-126+	--	10YR5/5	10YR6/5	vgS	m	so,po	0	8.0	S	so,po	II-
	RC-36	A	0-7	c,s	10YR3/2	10YR4/2	sgL	2gr	so,po	0	7.3	LS	so,po	0
		B1t	7-16	c,s	7.5YR4/3	7.5YR4/3	sgSCL+	2msbk	s,p	1npf	7.1	LS	so,po	0
		B2tca	16-25	a,s	10YR4/4	10YR5/5	sgSCL	3m-csbk	s,p	2npf	7.5	LS	so,po	I
		B3tca	25-35	g,s	10YR5/3	10YR6/3	sgL+	1fsbk, 1fpl	vs,vp	0	7.9	LS	so,po	II+
		K	35-53	g,s	2.5Y7/3	2.5Y8/2	gCL	2mpl	vs,vp	0	8.0	LS	so,po	III
		2C$_1$ca	53-80	c,s	2.5Y6/3.5	2.5Y7/3	gL	m	s,p	0	8.3	LS	so,po	II
		3C$_2$ca	80-103	d	2.5Y6/3	2.5Y7/3	sgCL	m	vs,p	0	8.3	CL	vs,p	II
		3C$_3$ca	103-173	g,s	2.5Y6/3	2.5Y6.5/3	sgSiC-	m	vs,vp	0	8.4	SiCL-	vs,vp	I
		3-4C$_4$ca	173-200	g,s	10YR5/4	10YR6/3.5	sgL	m	ss,ps	0	8.5	L	ss,ps	I
		4C$_5$ca	200-227	d	10YR5/3.5	1.25Y7/4	vgLS	m	so,po	0	8.6	LS	so,po	I+
		4C$_6$ca	227-255+	--	10YR5/4	1.25Y7/4	vgLS	m	so,po	0	8.4	LS	so,po	I-
Mesa	RC-33	A1	0-9	g,s	10YR3/2	10YR5/2	sgL+	2gr	ss,ps	0	6.4	LS	so,po	0
2,000		A3	9-16	g,s	10YR2.5/2	10YR4/2	sgCL	2gr,2fsbk	s,p	0	6.6	LS	so,po	0
		B1t	16-24	g,s	10YR3/2	10YR4/2.5	sgCL+	2fsbk	vs,vp	3npf	6.6	SL	so,po	0
		B2t	24-43	g or a,w	10YR3/3	8.75YR4/3	sgC-	2csbk	vs,vp	3mkpf	6.9	SL	so,po	0
		2B3t/ ca/K1	43-58	g/ c,w	10YR3/2 10YR6/3	10YR4/2.5 10YR7/3	gSCL-	1msbk/m	s,p	2npf	7.6	LS	so,po III	0/II/
		2K2	58-92	g,s	10YR7/2	10YR8/1	vgSL	m	s,ps	0	7.9	LS	so,po	III
		3C$_1$ca	92-180	g,s	2.5Y5/3	2.5Y7/3	vgSL	m	ss,po	0	8.2	LS	so,po	II
		3C$_2$ca	180-220+	--	10YR4/5	10YR6/5	vgSL	m	so,po	0	8.2	LS	so,po	I
	RC-8	A	0-8	c,s	10YR3/3	10YR3/4	gSCL	2gr	s,p	0	7.2	SL	so,po	0
		B2t	8-22	a,w	7.5YR4/4	7.5YR4/3.5	gSCL+	3m-csbk	vs,vp	2mkpf	7.0	SL	so,po	0
		2B3tca	22-72	g,s	10YR5/4	10YR6.5/3	vgSCL	1m-csbk	vs,p	1npf	7.5	LS	so,po	II/III
		2K	72-112	d	10YR6/3	10YR8/1	vgLS	m	ss,ps	0	7.8	LS	so,po	III
		2Cca	112-162+	--	10YR5.5/3	10YR7/2.5	vgSL-	m	ss,po	0	7.8	LS	so,po	II+
Basin chronosequence														
Holocene	RC-46A	Ap	0-20	a,s	10YR3/2.5	2.5Y5.5/2	CL-	1fsbk	ss,ps	0	8.0	L	so,po	0
7		ACca	20-40	a,w	10YR4/2.5	10YR6/2.5	SL	1fsbk	ss,ps	0	8.1	SL	so,po	I
		2Cgca	40-70	c,s	2.5Y4/2	2.5Y6/2	CL-	m	so,po	0	8.1	L	ss,ps	I
		2Cox	70-98	a,w	2.5Y4/4	2.5Y6/3	L-	m	so,po	0	7.8	L	ss,ps	0
		3Cn	98-150+	--	2.5Y4/2	2.5Y6/2	vgLS	m	so,po	0	7.8	LS	so,po	0
	RC-46B	Apca	0-28	a,s	10YR3/2	2.5Y5/2	sgL+	1msbk	ss,po	0	7.9	L	so,po	I
		2Cca	28-60	a,w	10YR5/3	1.25Y6/2	gSL	1fsbk	ss,po	0	8.0	SL	so,po	I
		3Cn	60-150+	--	2.5Y4/2	2.5Y6/2	vgLS	m	so,po	0	7.8	LS	so,po	0
Pinedale	RC-20	A	0-9	c,s	10YR4/3	10YR6/3	sgL	2gr	ss,ps	0	7.0	SL	so,po	0
20		2B1t	9-15	g,s	10YR3.5/4	10YR5/4	gSCL	2fsbk	s,p	1npf	7.4	LS	so,po	0
		2B2tca	15-32	a,w	10YR4/4	10YR4/4	gSCL-	2msbk	s,p	1npf	7.7	LS	so,po	I
		2B3tca	32-50	g,s	10YR5/4	10YR6/4	vgLS	1fsbk	ss,po	0	8.3	LS	so,po	I
		3C$_1$ca	50-130	d	10YR5/4	10YR6.5/4	vgS+	m	so,po	0	8.6	S	so,po	II-
		3C$_2$ca	130-330+	--	2.5Y5/3	2.5Y7/3	vgS	m	so,po	0	8.9	S	so,po	I
	RC-43	A	0-18	c,s	10YR4/2	10YR5/3	sgCL-	2fpl, 1msbk	ss,ps	0	7.3	L	ss,ps	0
		B1t	18-33	g,s	10YR3.5/2	10YR5/2.5	sgL	2msbk	ss,ps	0	7.7	L	ss,ps	0
		B2t	33-44	c,s	10YR3.5/3	10YR4/3.5	gCL	2msbk	s,p	0	7.8	L	ss,ps	0
		2B3tca	44-65	g,s	10YR4/3	10YR5.5/3	vgSL	1f-msbk	ss,ps	0	8.1	LS	so,po	II
		2C$_1$ca	65-98	d	10YR5/3	10YR5.5/3	vgS	m	so,po	0	8.2	S	so,po	II
		3C$_2$ca	98-200+	--	2.5Y5/3	2.5Y6/3	vgS	m	so,po	0	8.4	S	so,po	I
Bull Lake	RC-27	A	0-6	c,s	10YR4/3	10YR6/2.5	vsgL+	2mpl	so,ps	0	7.9	SL	so,po	I
120		2B1t	6-11	g,s	10YR3/2	10YR5/3	gL+	2msbk	ss,p	1npf	7.5	LS	so,po	I-
		2B2t	11-19	a,w	10YR4/3	10YR4/3	vgCL-	1fsbk	s,p	1npf	7.5	LS	so,po	0
		3B3ca	19-34	g,s	10YR5/3	10YR7/2	L+	2mabk	s,p	0	7.8	L	ss,ps	II
		3C$_1$ca	34-74	a,s	2.5Y5/3	2.5Y7/2.5	L+	m	s,p	0	7.8	L	ss,ps	I+
		4C$_2$ca	74-147	c,s	2.5Y5/2.5	2.5Y6/2.5	vsgL	m	so,po	0	8.6	L	so,po	I
		5C$_3$ca	147-225+	--	10YR5/3	10YR6/3	vgLS	m	so,po	0	7.9	LS	so,po	I

Supplementary table 1, part 2. Field descriptions--Continued

Surface and age, ka	Sample number	Horizon	Depth (cm)	Lower boundary	Moist color	Dry color	Texture	Structure	Wet consistence	Clay films	pH	Assumed parent material (<2 mm)		Stage $CaCO_3$
												Texture	Wet consistence	
Boyd 415	RC-23	A	0-3	c,s	10YR3/2	10YR5/3	vsgSiL	2gr	so,ps	0	6.7	SL	so,po	0
		B1tca	3-7	g,s	10YR3/3	10YR4.5/3	vsgL	1msbk	ss,ps	1npf	7.2	LS	so,po	I
		B2tca	7-14	g,s	10YR3/2	10YR5/3	sgL+	2msbk	s,p	1npf	7.4	LS	so,po	I
		B3tca	14-29	a,s	10YR4/3	10YR5.5/3	gSL+	1f-msbk	s,p	0	7.5	LS	so,po	II
		2K	29-60	c,w	2.5Y7/3	2.5Y8/2	vgLS	m	s,ps	0	7.8	LS	so,po	III
		$3C_1ca$	60-121	g,s	10YR5/4	10YR7/4	vgSL	m	so,po	0	7.8	S	so,po	II
		$3C_2ca$	121-170	c,w	10YR5/5	10YR6/5	vgLS	m	so,po	0	7.8	S	so,po	I
		$4C_3ca$	170-226	g,s	10YR5.5/4	10YR7/4	vgSL-	m	so,po	0	8.0	LS	so,po	II
		$5C_4ca$	226-255	c,w	10YR5/5	10YR6/6	vgS	m	so,po	0	8.0	S	so,po	I
		$5C_5ca$	255-310	g,s	10YR6/3.5	10YR7/4	vgLS	m	so,po	0	8.0	LS	so,po	II
		$5C_6ca$	310+	--	10YR5/5	10YR6/6	vgS	m	so,po	0	0	S	so,po	I
Lower Roberts 600	RC-24	A	0-4	c,s	10YR3/2	10YR5/2.5	sgCL	2gr	s,p	0	6.4	SL	so,po	0
		B1t	4-9	c,s	10YR3/3	10YR4/2.5	sgCL	3msbk, 1fpl	vs,p	1npf	6.7	SL	so,po	0
		B2tca	9-19	g,s	10YR4/3	10YR5/3	sgSiCL	3msbk, 2fpl	vs,vp	2mkpf	7.4	SL	so,po	I
		B3tca	19-30	c,s	10YR5/3	10YR6/3	sgSiL+	2f-msbk, 1fpl	vs,vp	1npf	8.0	SL	so,po	II
		K	30-45	g,s	2.5Y8/3	10YR8/1	sgCL-	2mpl,m	s,p	0	8.0	LS	so,po	III
		$2C_1ca$	45-62	g,s	10YR6/3	10YR7/3	vgSL	m	ss,po	0	8.3	LS	so,po	II+
		$2C_2ca$	62-87	g,s	10YR5/4	10YR6/3.5	vgS	m	so,po	0	8.5	S	so,po	II-
		$2C_3ca$	87-300+	--	10YR6/3.5	10YR8/3.5	vgS	m	so,po	0	8.7	S	so,po	I
Upper Roberts 945	RC-25	Aca	0-4	g,s	10YR3/2	10YR4/2	sgL	2gr	so,ps	--[2]	7.4	SL	so,po	II
		B1tca	4-9	g,s	10YR 3.5/2.5	10YR5/2.5	sgL	2fsbk	so,ps	--	7.3	SL	so,po	II
		B2tca	9-15	g,s	10YR4/2.5	10YR5/2.5	sgL+	2f-msbk	s,p	--	7.4	SL	so,po	II
		B3tca	15-25	a,s	10YR4/3	10YR6/3	sgL	1fsbk	s,p	--	7.4	LS	so,po	II+
		2K	25-49	g,w	10YR6/2.5	10YR8/1	gSL	m	vs,vp	--	7.6	LS	so,po	III
		$2C_1ca$	49-65	g,w	10YR6/2	10YR7/2	vgSL+	m	s,p	--	7.9	LS	so,po	II+
		$2C_2ca$	65-91	a,w	10YR5/2	10YR6/2	vgLS	m	ss,po	--	8.1	LS	so,po	II
		$3C_3ca$	91-130+	--	10YR4/3	10YR5.5/3	gSL	m	s,sp	--	8.4	SL	s,sp	II
	RC-44	Aca	0-6	g,s	10YR3/2	10YR5/2	sgL	1gr	ss,ps	0	7.5	SL	so,po	II
		B1tca	6-13	g,s	10YR3/3	10YR4/3	gCL	2f-msbk	s,ps	0	7.5	SL	so,po	II
		B21tca	13-19	c,s	10YR4/3	10YR6/3	gCL	2msbk	s,p	0	7.8	LS	so,po	II
		B22tca	19-27	g,s	10YR5.5/3	10YR6.5/3	gL	2m-csbk	s,ps	0	7.9	LS	so,po	II+
		2B31tca	27-45	c,s	10YR6/3	10YR8/2	gL	2f-msbk	ss,ps	0	7.9	S	so,po	III
		2B32tca	45-86	c,s	10YR5/3.5	10YR5/3	vgSL	1fsbk	ss,ps	0	8.3	S	so,po	II+
		2Cca	86-120+	--	10YR4/4	10YR5/3	vgLS-	m	so,po	0	8.6	S	so,po	I
Mesa 2,000	RC-26A	A	0-6	c,s	10YR3/2	10YR6/3	sgL	1gr,1fpl	so,ps	0	6.6	SL	so,po	0
		B1t	6-11	g,s	10YR3/2	10YR4/2.5	sgL+	2msbk	s,p	3npf	6.9	SL	so,po	0
		B21t	11-20	g,s	10YR 3.5/2.5	10YR4/3	sgL+	3csbk, 2mpr	vs,vp	3mkpf	7.0	SL	so,po	0
		B22tca	20-29	c,w	10YR4/3	10YR5/3	sgL+	2msbk, 1mpr	vs,vp	2npf	7.4	SL	so,po	I
		B3tca	29-40	c,s	10YR5/3	10YR6/3	gL+	m	s,p	0	7.9	LS	so,po	II
		2K	40-68	c,w	10YR7/3	10YR8/1	gSL	m	vs,vp	0	7.9	S	so,po	III
		$2C_1ca$	68-145	c,w	10YR7/3	10YR8/2.5	vgLS	m	ss,ps	0	8.9	S	so,po	II+
		$2C_2ca$	145-247	d	10YR6/3.5	10YR8/3.5	vgS	m	so,po	0	8.9	S	so,po	II
		$2C_3ca$	247-295	a,w	10YR6/4	10YR7/3.5	vgS	m	so,po	0	8.6	S	so,po	I
		R	295+	--	--	--	--	--	--	--	--	--	--	--
	RC-26B	A	0-5	c,s	10YR3/2	10YR5/3	sgL	1gr,1fpl	so,ps	0	6.8	SL	so,po	0
		B1t	5-10	g,s	10YR3/2	10YR4/2.5	sgL+	2msbk	s,p	3npf	6.8	SL	so,po	0
		B2tca	10-16	a,s	10YR4/3.5	10YR5/4	sgCL	3msbk, 1mpr	vs,vp	3mkpf	7.1	SL	so,po	I-
		B31tca	16-25	g,w	10YR5/3	10YR6.5/3	vsgSCL-	2msbk	s,vp	2npf	7.4	LS	so,po	I
		B32tca	25-36	c,w	10YR6/3	10YR7/2.5	sgSL+	1fsbk	s,p	1npf	7.5	LS	so,po	II
		2K	36-48	g,s	10YR7/3	10YR8/1	gSL	m	s,p	0	7.6	S	so,po	III
		2C1ca	48-88	g,s	10YR7/3	10YR8/2.5	vgS	m	ss,po	0	7.9	S	so,po	II+
		$2C_2ca$	88-170+	--	2.5Y6/3	2.5Y8/3	vgS	m	so,po	0	8.2	S	so,po	II

Supplementary table 1, part 2. Field descriptions--Continued

KEY[1]

SOIL STRUCTURE

Grade	Size	Type
m, massive	vf, very fine (v thin)	gr, granular
sg, single grained	f, fine (thin)	pl, platey
1, weak	m, medium	pr, prismatic
2, moderate	c, coarse (thick)	cpr, columnar
3, strong	vc, very coarse (very thick)	abk, angular blocky
		sbk, subangular blocky

If two structures, listed as primary and secondary

SOIL TEXTURE

vsg, very slightly gravelly (<5%)	co, coarse	S, sand	SCL, sandy clay loam
sg, slightly gravelly (5-20%)	f, fine	LS, loamy sand	CL, clay loam
g, gravelly (20-50%)	vf, very fine	SL, sandy loam	SiCL, silty clay loam
vg, very gravelly (>50%)		L, loam	SC, sandy clay
		SiL, silt loam	C, clay
		Si, silt	SiC, silty clay

SOIL CONSISTENCE

Wet	
so, non-sticky	po, non-plastic
ss, slightly sticky	ps, slightly plastic
s, sticky	p, plastic
vs, very sticky	vp, very plastic

HORIZON BOUNDARIES

Distinctness	Topography
va, very abrupt	s, smooth
a, abrupt	w, wavy
c, clear	i, irregular
g, gradual	b, broken
d, diffuse	

CLAY FILMS

Frequency	Thickness	Morphology
v_1, very few	n, thin	pf, ped face coatings
1, few	mk, moderately thick	br, bridging grains
2, common	k, thick	po, pore linings
3, many		(w, occurs as waves or lamellae)
4, continuous		co, coats on clasts

STAGES OF $CaCO_3$[2]

Roman numerals indicate increasing content of $CaCO_3$.

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[1]For more detailed information, see Soil Survey Staff (1975) and Birkeland (1984).
[2]For more detailed information, see Bachman and Machette (1977).

Supplementary table 2. Physical properties

[Analysts: M.C. Reheis and D.M. Cheney, U.S. Geological Survey. --, not measured]

Methods

Bulk density was determined by two different methods (Blake, 1965). Two to four paraffin-coated peds taken from relatively fine textured horizons provided mean bulk densities for A, B, K, and some C horizons. Bulk density was measured on many gravelly C horizons in the field by weighing an excavated amount of soil and measuring the volume of the hole with water-filled plastic bags. For C horizons not measured by either of these methods, bulk density was estimated by comparison to horizons with similar gravel content.

Gravel percent by volume was visually estimated for all horizons. Gravel was separated and weighed from bulk samples of finer textured horizons to obtain weight percent of gravel as a check on the visual estimate.

Particle size of the <2-mm fraction was obtained by methods described in Day (1965). All samples were pretreated to remove organic matter by gentle heating in a weak solution of hydrogen peroxide. Carbonates were removed from samples by gentle heating in a weak solution of sodium acetate. The sand fraction was separated by wet sieving; the dried sand was weighed and dry-sieved to obtain the various sand fractions. Silt and clay fractions were obtained by the pipette method except for the dust-trap sample, for which there was insufficient material after removal of $CaCO_3$. Sand was removed from the dust-trap sample by wet sieving, and silt and clay fractions were determined on the remaining sediment using the 5000b Sedigraph Analyzer (analyses by R. Kihl, Institute of Arctic and Alpine Research, Boulder, Colo.).

No.	Age (ka)	Sample No.	Horizon	Basal depth (cm)	>2mm (%)	Percent of <2-mm fraction: Total sand	vco sand	co sand	med sand	fi sand	vfi sand	Total silt	<2μ clay	<1μ clay	Bulk density (g/cm³)	percent of <2-mm fraction: co silt	med silt	vfi silt	co clay silt(2-.05μ)	fi clay (<0.5μ)
1	0	RC-R	Channel gravel		--	98.82	49.95	29.85	11.64	6.59	0.78	0.41	0.77	0.00	--	0.41	0.00	0.00	--	--
2	0	RC-M	Channel gravel		--	91.25	23.18	32.92	16.31	16.38	2.47	5.50	3.25	3.25	--	3.89	1.01	0.60	--	--
						Mountain-front chronosequence														
3	7	RC-38	A1	9	15	81.31	27.83	22.91	12.59	15.09	2.86	15.32	3.37	3.11	1.18	8.45	4.88	1.98	--	--
4	7	RC-38	2A31	22	40	81.93	34.43	19.15	10.48	13.69	4.18	14.32	3.75	3.05	1.75	8.61	4.06	1.65	--	--
5	7	RC-38	2A32	33	50	84.76	34.27	20.59	11.37	14.58	3.95	12.30	2.94	2.94	1.50	7.94	3.22	1.14	--	--
6	7	RC-38	2AC	46	40	86.03	34.39	21.63	11.40	14.73	3.88	11.79	2.18	2.18	1.50	7.47	3.20	1.13	--	--
7	7	RC-38	3C1ox	85	65	84.82	29.76	24.64	11.99	14.44	4.00	13.46	1.72	1.49	1.90	8.81	3.35	1.30	--	--
8	7	RC-38	3C2ox	+120	80	80.82	24.10	24.03	12.31	15.61	4.77	16.84	2.34	2.34	1.80	10.27	5.06	1.51	--	--
9	20	RC-21	A	5	5	54.24	10.41	14.61	9.23	15.14	4.84	33.25	12.51	10.37	1.47	17.18	11.52	4.55	--	--
10	20	RC-21	B1t	12	5	54.69	13.76	12.27	8.52	14.85	5.28	31.45	13.86	11.24	1.65	16.29	10.98	4.18	--	--
11	20	RC-21	B2t	25	15	51.61	11.99	10.68	7.93	15.17	5.85	31.11	17.28	15.21	1.60	16.88	10.37	3.86	--	--
12	20	RC-21	2B3t	38	25	65.38	17.56	13.52	10.37	18.66	5.27	20.70	13.92	12.97	1.74	10.88	7.04	2.78	--	--
13	20	RC-21	3C1ox	73	85	94.51	32.47	31.47	16.18	12.46	1.93	4.70	0.79	0.79	1.80	3.59	0.78	0.34	--	--
14	20	RC-21	3C2ox	+110	85	96.70	18.52	25.81	22.95	25.59	3.82	2.77	0.53	0.53	1.80	2.50	0.27	0.00	--	--
15	20	RC-15	A	8	5	64.84	8.04	15.61	17.95	--	--	25.14	--	--	--	--	--	--	3.71	6.31
16	20	RC-15	2B2t	23	60	77.16	17.71	18.29	19.97	--	--	15.20	--	--	--	--	--	--	2.49	5.13
17	20	RC-15	2B3	43	70	85.93	24.79	20.74	21.62	--	--	9.26	--	--	--	--	--	--	1.56	3.25
18	20	RC-15	2Cox	+68	80	94.77	29.08	29.50	22.55	--	--	3.57	--	--	--	--	--	--	0.56	1.10
19	120	RC-31	A1	8	20	67.56	24.91	16.19	9.32	13.70	3.45	21.58	10.86	1.81	1.31	13.01	7.34	1.23	--	--
20	120	RC-31	A3	19	25	65.92	24.29	14.96	8.81	13.46	4.40	22.52	11.56	9.64	1.53	12.86	8.23	1.43	--	--
21	120	RC-31	B1t	32	35	56.24	18.78	11.17	7.26	13.47	5.57	27.61	16.15	15.06	1.69	16.45	9.13	2.03	--	--
22	120	RC-31	B21t	54	25	60.54	21.50	13.10	7.29	13.52	5.13	24.71	14.75	13.02	1.82	15.16	7.83	1.73	--	--
23	120	RC-31	B22t	81	30	65.06	20.29	15.65	9.92	14.48	4.72	16.52	18.42	16.95	1.78	9.92	6.05	0.55	--	--
24	120	RC-31	2B31t	123	35	81.00	29.16	20.75	11.60	15.00	4.49	12.18	6.82	6.29	1.97	7.32	4.52	0.34	--	--
25	120	RC-31	2B32t	145	60	86.08	30.89	23.56	12.49	15.12	4.02	9.59	4.33	4.17	1.94	5.77	3.62	0.20	--	--
26	120	RC-31	2Cox	+200	70	91.84	32.04	27.33	14.10	14.88	3.50	5.94	2.22	1.84	1.94	4.11	1.83	0.00	--	--
27	120	RC-17	A	9	5	49.38	6.00	9.27	11.00	--	--	32.69	--	--	--	--	--	--	5.27	12.66
28	120	RC-17	B1t	20	15	51.33	5.37	7.76	11.22	--	--	27.88	--	--	--	--	--	--	6.01	14.78
29	120	RC-17	B2t	31	20	55.60	7.50	9.94	12.56	--	--	24.11	--	--	--	--	--	--	4.92	15.37
30	120	RC-17	B31t	50	30	66.93	11.42	15.31	15.91	--	--	15.84	--	--	--	--	--	--	3.73	13.50
31	120	RC-17	2B32t	122	60	83.49	14.82	27.04	23.50	--	--	10.67	--	--	--	--	--	--	1.27	4.57
32	120	RC-17	2Cox	+136	80	86.75	21.46	24.72	20.73	--	--	9.41	--	--	--	--	--	--	1.28	2.56
33	415	RC-30	A1	9	10	69.53	26.28	18.01	9.52	12.07	3.66	20.25	10.22	6.65	1.26	11.99	6.14	2.12	--	--
34	415	RC-30	A3	17	20	74.74	33.72	17.65	8.95	11.00	3.42	16.22	9.04	8.65	1.60	8.15	6.17	1.90	--	--
35	415	RC-30	B1t	29	20	66.49	25.39	15.48	8.80	12.45	4.38	21.50	12.01	11.37	1.58	13.65	4.57	3.29	--	--
36	415	RC-30	B2t	53	35	70.59	27.89	17.37	8.70	12.61	4.02	13.11	16.30	15.53	1.82	8.88	4.12	0.12	--	--
37	415	RC-30	2B31t	81	35	73.55	27.68	19.67	10.53	12.40	3.27	11.16	15.29	15.14	1.85	5.74	3.69	1.73	--	--
38	415	RC-30	2B32t	170	40	82.97	28.05	25.62	13.19	13.26	2.84	6.41	10.62	10.62	1.93	4.08	0.92	1.40	--	--
39	415	RC-30	2Cox	+250	60	86.95	37.99	28.69	9.66	8.54	2.07	4.91	8.14	7.92	1.84	3.16	0.90	0.85	--	--
40	600	RC-29	A1	9	35	65.87	24.65	16.09	9.06	12.12	3.95	22.88	11.25	9.83	1.26	12.07	7.81	2.99	--	--
41	600	RC-29	A3	18	35	70.19	26.08	18.17	9.63	12.60	3.71	19.07	10.74	10.62	1.52	10.33	5.52	3.23	--	--
42	600	RC-29	B1t	30	20	63.36	23.23	15.36	8.41	12.23	4.15	22.10	14.54	13.24	1.60	12.54	6.59	2.96	--	--
43	600	RC-29	B2t	50	40	64.88	24.58	15.36	8.56	12.07	4.30	20.91	14.21	13.29	1.75	12.18	6.02	2.71	--	--
44	600	RC-29	2B31t	79	40	72.64	29.56	16.42	9.21	13.27	4.18	16.62	10.74	10.37	1.74	9.62	4.00	3.01	--	--
45	600	RC-29	3B32t	167	40	81.55	22.81	23.64	12.59	16.96	5.55	11.23	7.22	6.93	2.06	6.95	3.13	1.14	--	--
46	600	RC-29	3Cox	+260	65	84.29	30.52	24.65	12.61	13.72	2.79	5.64	10.07	9.85	1.88	3.74	0.94	0.96	--	--
47	600	RC-16	A	27	10	73.84	18.97	20.13	16.5	--	--	14.47	--	--	--	--	--	--	2.82	8.87
48	600	RC-16	B1t	47	20	68.11	13.72	16.73	15.38	--	--	14.89	--	--	--	--	--	--	3.21	13.79
49	600	RC-16	2B2t	72	40	76.65	16.70	21.19	19.03	--	--	9.13	--	--	--	--	--	--	1.71	12.51
50	600	RC-16	2B3t	127	50	71.98	8.40	13.35	19.79	--	--	11.88	--	--	--	--	--	--	3.50	12.64
51	600	RC-16	2Cox	+197	65	86.55	19.78	30.77	22.30	--	--	6.03	--	--	--	--	--	--	1.61	5.81

Supplementary table 2. Physical properties--Continued

No.	Age (ka)	Sample No.	Horizon	Basal depth (cm)	>2mm (%)	Total sand	vco sand	co sand	med sand	fi sand	vfi sand	Total silt	<2µ clay	<1µ clay	Bulk density (g/cm^3)	co silt	med silt	vfi silt (2-.05µ)	co clay	fi clay (<0.5µ)
						Percent of <2-mm fraction										percent of <2-mm fraction				
52	2,000	RC-28	A	7	30	73.32	31.84	18.29	8.54	11.10	3.55	17.88	8.80	8.27	1.26	9.64	5.79	2.46	--	--
53	2,000	RC-28	B1t	11	20	77.03	32.11	19.27	9.79	12.09	3.83	13.99	8.98	8.20	1.53	6.90	5.49	1.55	--	--
54	2,000	RC-28	B2t	17	25	74.17	28.22	19.08	10.09	12.86	3.92	14.20	11.63	10.70	1.64	7.95	4.53	1.73	--	--
55	2,000	RC-28	2B31t	47	60	76.66	26.65	21.91	9.90	13.93	4.28	12.07	11.27	10.00	1.88	6.76	4.08	1.23	--	--
56	2,000	RC-28	2B32t	141	60	83.22	28.56	28.27	12.07	11.44	2.89	7.63	9.15	8.18	1.98	4.16	2.82	0.66	--	--
57	2,000	RC-28	2Cox	+270	70	89.55	27.65	31.38	17.49	11.36	1.67	3.59	6.86	6.55	1.93	1.81	1.56	0.22	--	--
58	2,000	RC-14	A	17	5	56.46	9.32	13.99	12.49	--	--	25.01	--	--	1.32	--	--	--	5.35	13.18
59	2,000	RC-14	B1t	32	5	55.84	9.96	12.62	11.73	--	--	23.06	--	--	1.52	--	--	--	5.88	15.52
60	2,000	RC-14	B2t	44	10	60.02	12.29	14.66	12.49	--	--	19.70	--	--	1.79	--	--	--	4.53	15.75
61	2,000	RC-14	2B31t	84	40	72.86	13.47	20.53	17.93	--	--	12.92	--	--	1.88	--	--	--	2.57	11.65
62	2,000	RC-14	3B32t	144	50	81.19	20.61	26.97	18.94	--	--	7.54	--	--	1.98	--	--	--	1.70	9.57
63	2,000	RC-14	3Cox	+164	70	89.29	18.11	31.20	24.19	--	--	6.09	--	--	1.93	--	--	--	0.98	3.64
									Transition chronosequence											
64	7	RC-40	A	13	5	59.32	1.74	6.30	12.58	--	--	26.68	--	--	1.48	--	--	--	4.43	9.57
65	7	RC-40	Bs	46	30	62.08	4.19	9.57	14.26	--	--	23.18	--	--	1.68	--	--	--	4.40	10.34
66	7	RC-40	2C1ox	75	70	88.39	6.12	25.26	42.74	--	--	4.72	--	--	1.88	--	--	--	0.59	6.30
67	7	RC-40	2C2ox	310	75	93.45	5.74	39.14	36.48	--	--	3.02	--	--	1.88	--	--	--	0.26	3.27
68	7	RC-42	A1	6	30	58.17	4.17	11.91	10.92	22.85	8.32	32.95	8.88	7.71	1.44	22.85	7.67	2.43	--	--
69	7	RC-42	A3	37	40	61.32	5.33	13.08	11.52	23.61	7.78	29.68	9.00	7.36	1.45	20.37	6.25	3.07	--	--
70	7	RC-42	2Bs	55	10	62.92	5.72	12.92	11.13	24.25	8.89	26.95	10.13	8.31	1.48	17.95	4.09	4.91	--	--
71	7	RC-42	3Bb	73	50	66.02	8.69	19.67	12.50	18.27	6.89	24.07	9.91	7.94	1.50	15.82	5.93	2.31	--	--
72	7	RC-42	3Coxb	+200	75	93.59	26.48	33.73	18.67	13.02	1.69	4.32	2.09	1.85	1.88	3.11	0.76	0.45	--	--
73	20	RC-22	A	5	5	50.81	7.68	14.16	8.08	14.63	6.27	36.40	12.79	9.95	1.35	22.45	9.68	4.27	--	--
74	20	RC-22	B1t	25	20	55.00	10.57	16.23	8.81	13.96	5.43	31.96	13.04	10.58	1.52	18.98	9.46	3.52	--	--
75	20	RC-22	B2t	43	35	55.06	10.60	18.05	9.52	11.90	4.98	28.63	16.31	14.16	1.75	16.18	9.20	3.26	--	--
76	20	RC-22	2B3t	57	75	75.67	26.00	24.88	11.00	10.89	2.91	14.90	9.43	7.99	1.69	8.99	5.03	0.88	--	--
77	20	RC-22	2C1ox	78	75	84.85	27.23	28.24	14.28	12.81	2.29	8.43	6.72	6.21	1.80	5.56	2.61	0.26	--	--
78	20	RC-22	2C2ox	175	60	84.04	24.91	25.38	16.84	14.54	2.38	10.21	5.75	5.72	1.88	4.73	4.47	1.00	--	--
79	20	RC-22	3Cca	197	80	88.62	36.30	28.06	11.45	10.49	2.33	7.29	4.09	4.09	2.11	3.76	3.04	0.48	--	--
80	20	RC-22	3Cn	+240	80	90.37	9.65	27.58	20.08	27.01	6.06	6.80	2.83	2.54	1.80	5.47	1.22	0.10	--	--
81	120	RC-12	A	9	5	47.07	7.21	11.17	9.38	--	--	33.75	--	--	--	--	--	--	7.45	11.73
82	120	RC-12	B1t	17	15	42.73	5.81	9.09	9.97	--	--	27.91	--	--	--	--	--	--	7.82	21.54
83	120	RC-12	B2t	39	25	66.74	17.61	23.12	14.15	--	--	7.46	--	--	--	--	--	--	3.12	22.68
84	120	RC-12	2B3t	62	50	76.45	21.59	26.51	16.34	--	--	6.25	--	--	--	--	--	--	2.81	14.49
85	120	RC-12	2Cox	+122	80	89.36	23.33	33.53	21.88	--	--	3.19	--	--	--	--	--	--	0.82	6.63
86	120	RC-32	Ap	21	5	22.06	4.13	3.97	3.28	7.61	3.06	31.35	46.59	41.49	1.70	13.55	10.15	7.65	--	--
87	120	RC-32	2B2tca	37	40	54.40	19.21	16.26	7.69	8.66	2.58	18.83	26.77	24.19	1.67	7.62	8.21	3.01	--	--
88	120	RC-32	2B3tca	70	15	59.59	15.88	16.47	9.97	13.49	3.78	20.63	19.78	17.76	1.62	11.93	6.14	2.55	--	--
89	120	RC-32	3Cca	+80	80	87.37	26.72	37.86	13.34	8.12	1.32	7.17	5.46	4.31	1.85	3.96	2.08	1.13	--	--
90	120	RC-41	A	8	20	54.73	13.56	11.87	7.13	15.01	7.15	34.69	10.58	7.28	1.33	21.84	9.57	3.28	--	--
91	120	RC-41	B1t	17	30	46.80	12.39	9.53	6.43	12.87	5.59	33.21	19.99	14.67	1.73	17.31	11.11	4.79	--	--
92	120	RC-41	B2t	28	30	44.76	13.77	9.52	6.49	10.98	4.00	21.87	33.37	30.38	1.64	12.60	6.80	2.47	--	--
93	120	RC-41	2B31t	51	45	70.76	30.19	18.93	8.94	9.90	2.79	7.35	21.89	21.69	1.75	5.29	1.88	0.19	--	--
94	120	RC-41	2B32t	65	65	75.93	36.45	22.48	8.03	6.88	2.10	6.94	17.13	15.89	1.90	4.82	0.89	1.24	--	--
95	120	RC-41	2Cox	+100	80	91.95	47.70	34.26	6.43	2.83	0.74	1.67	6.38	6.12	1.85	1.04	0.00	0.64	--	--
96	415	RC-11	A	9	30	70.31	10.46	18.81	18.92	--	--	16.89	--	--	--	--	--	--	3.44	9.36
97	415	RC-11	B2t	20	40	63.20	11.83	17.21	16.32	--	--	11.50	--	--	--	--	--	--	3.51	21.79
98	415	RC-11	B3t	50	40	76.46	23.50	23.28	15.86	--	--	7.84	--	--	--	--	--	--	1.99	13.71
99	415	RC-11	2C1ca	100	60	81.70	20.05	22.79	22.00	--	--	9.24	--	--	--	--	--	--	1.68	7.38
100	415	RC-11	2C2ca	+180	80	95.49	5.07	40.44	39.10	--	--	1.92	--	--	--	--	--	--	0.79	1.80
101	415	RC-37	A	6	5	56.39	9.76	13.59	10.58	16.83	5.63	29.53	14.08	11.96	1.35	16.51	7.71	5.31	--	--
102	415	RC-37	B1t	18	20	49.70	6.52	10.51	9.90	17.53	5.24	30.67	19.63	17.75	1.63	17.03	9.39	4.25	--	--
103	415	RC-37	B2tca	45	15	57.88	5.31	9.94	12.08	23.90	6.66	21.05	21.07	19.95	1.71	12.48	5.50	3.07	--	--
104	415	RC-37	B3tca/K	63	5	49.32	3.65	14.79	9.39	15.45	6.05	21.16	29.52	28.80	1.23	14.48	3.72	2.95	--	--
105	415	RC-37	2C1ca	109	45	59.42	14.68	19.50	9.57	11.74	3.94	21.35	19.23	19.23	1.49	12.80	5.67	2.88	--	--
106	415	RC-37	3C2ca	230	70	88.55	18.29	39.94	17.60	10.86	1.86	6.21	5.24	5.24	1.94	3.56	1.20	1.45	--	--
107	415	RC-37	3C3ca	+240	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
108	600	RC-34	A1	8	10	52.77	15.88	13.15	7.42	11.20	5.12	32.09	15.14	11.78	1.61	19.89	10.01	2.19	--	--
109	600	RC-34	A3	14	10	54.04	16.33	13.85	7.67	11.31	4.88	31.63	14.33	13.18	1.61	18.66	9.47	3.50	--	--
110	600	RC-34	B1t	22	10	52.53	15.15	13.25	7.67	11.45	5.02	32.19	15.28	14.15	1.64	19.13	9.93	3.14	--	--
111	600	RC-34	B2t	37	20	50.22	16.09	11.40	6.51	10.86	5.36	29.45	20.33	20.32	1.67	18.02	7.91	3.53	--	--
112	600	RC-34	2B3t/ca	54	50	74.45	31.65	17.03	8.46	12.67	4.65	15.30	10.25	10.25	1.83	9.53	4.38	1.38	--	--
113	600	RC-34	3Cox/ca	89	60	84.14	23.35	24.81	13.90	17.14	4.94	11.48	4.38	4.38	1.74	7.41	3.30	0.77	--	--
114	600	RC-34	3C1ca	160	80	93.01	33.53	32.80	12.37	11.84	2.48	4.73	2.26	2.26	1.85	3.03	1.06	0.63	--	--
115	600	RC-34	3C2ca	+210	80	95.45	29.69	41.79	14.50	8.43	1.03	2.22	2.33	2.23	1.88	1.81	0.31	0.10	--	--

Supplementary table 2. Physical properties--Continued

No.	Age (ka)	Sample No.	Horizon	Basal depth (cm)	>2mm (%)	Total sand	vco sand	co sand	med sand	fi sand	vfi sand	Total silt	<2μ clay	<1μ clay	Bulk density (g/cm^3)	co silt	med silt	vfi silt(2-.05μ)	co clay	fi clay (<0.5μ)
						Percent of <2-mm fraction										percent of <2-mm fraction				
116	600	RC-35	A	5	5	62.28	8.11	11.13	17.16	--	--	24.79	--	--	1.39	--	--	--	3.88	9.05
117	600	RC-35	B1t	10	10	56.13	8.18	8.70	15.72	--	--	21.52	--	--	1.55	--	--	--	4.54	17.81
118	600	RC-35	B2tca	18	20	58.75	8.44	8.22	15.92	--	--	15.50	--	--	1.53	--	--	--	3.75	22.00
119	600	RC-35	B3tca	32	20	80.25	18.15	20.26	20.33	--	--	9.68	--	--	1.68	--	--	--	1.04	9.03
120	600	RC-35	2C1ca	54	70	85.34	31.49	20.49	18.32	--	--	7.71	--	--	1.63	--	--	--	1.36	5.59
121	600	RC-35	2C2ca	135	75	82.78	8.40	20.99	28.08	--	--	10.89	--	--	1.85	--	--	--	1.39	4.94
122	600	RC-35	2C3ca	225	80	93.11	8.12	20.49	41.51	--	--	5.78	--	--	1.80	--	--	--	0.44	0.67
123	600	RC-35	2C4ca	+235	80	94.05	6.63	25.93	40.56	--	--	4.65	--	--	1.80	--	--	--	0.65	0.65
124	945	RC-6	A	13	5	52.56	2.25	5.77	12.87	--	--	27.88	--	--	--	--	--	--	5.61	13.95
125	945	RC-6	B1t	30	10	53.84	3.40	7.55	14.72	--	--	22.83	--	--	--	--	--	--	4.21	19.12
126	945	RC-6	B2t	46	20	52.83	3.12	6.90	13.83	--	--	22.71	--	--	--	--	--	--	3.64	20.82
127	945	RC-6	2C1ca	96	60	83.20	21.59	22.75	18.76	--	--	10.50	--	--	--	--	--	--	1.77	4.53
128	945	RC-6	2C2ca	+126	75	93.01	10.21	35.68	35.46	--	--	5.07	--	--	--	--	--	--	0.85	1.07
129	945	RC-36	A	7	35	50.20	5.84	8.41	8.71	21.27	5.98	33.21	16.59	13.48	1.41	21.10	8.47	3.64	--	--
130	945	RC-36	B1t	16	25	49.62	5.44	7.34	9.73	21.89	5.22	18.39	31.99	29.13	1.48	9.52	6.65	2.22	--	--
131	945	RC-36	B2tca	25	35	53.06	3.41	7.01	10.47	25.61	6.55	19.88	27.06	25.06	1.57	10.92	6.64	2.32	--	--
132	945	RC-36	B3tca	35	5	47.07	3.33	5.21	7.87	22.63	8.02	28.72	24.21	22.01	1.56	17.59	7.90	3.23	--	--
133	945	RC-36	K	53	10	33.95	2.72	2.82	3.51	16.73	8.18	36.29	29.76	25.19	1.53	20.96	10.39	4.95	--	--
134	945	RC-36	2C1ca	80	75	40.66	6.57	3.93	2.79	17.85	9.52	36.01	23.33	19.43	1.48	20.84	10.06	5.11	--	--
135	945	RC-36	3C2ca	103	15	21.83	0.72	1.47	2.28	10.62	6.74	45.15	33.02	26.92	1.58	25.19	13.20	6.76	--	--
136	945	RC-36	3C3ca	173	5	8.44	0.21	0.49	0.61	3.54	3.59	50.95	40.61	33.05	1.67	23.67	17.59	9.69	--	--
137	945	RC-36	3C4ca	200	5	41.19	0.69	3.31	6.99	19.25	10.95	38.09	20.72	17.69	1.67	23.32	10.25	4.53	--	--
138	945	RC-36	4C5ca	227	75	80.10	18.83	24.78	16.38	16.09	4.03	12.95	6.95	5.64	1.85	8.49	1.12	3.35	--	--
139	945	RC-36	4C6ca	+255	85	82.31	30.13	26.01	11.82	11.83	2.52	11.27	6.42	5.38	1.85	6.73	2.48	2.06	--	--
140	2,000	RC-33	A1	9	45	45.02	17.74	10.34	5.15	8.27	3.52	31.13	23.85	20.38	1.42	15.79	10.01	5.33	--	--
141	2,000	RC-33	A3	16	30	38.85	12.84	9.58	5.05	8.14	3.25	27.84	33.31	30.80	1.53	13.62	9.19	5.03	--	--
142	2,000	RC-33	B1t	24	20	33.66	10.91	8.24	4.44	7.34	2.74	27.30	39.04	36.97	1.60	13.32	8.62	5.35	--	--
143	2,000	RC-33	B2t	43	5	35.89	12.56	8.83	4.80	7.26	2.44	23.38	40.73	40.25	1.58	10.55	9.33	3.49	--	--
144	2,000	RC-33	2B3t/ca	58	45	48.48	16.95	11.94	6.69	9.83	3.08	23.64	27.88	26.70	1.49	12.12	7.10	4.42	--	--
145	2,000	RC-33	2K1	58	45	71.00	22.30	18.73	11.22	14.76	4.00	13.64	15.36	15.36	1.49	8.39	3.61	1.63	--	--
146	2,000	RC-33	2K2	92	45	73.95	30.33	19.97	9.86	10.90	2.88	11.66	14.39	13.69	1.71	6.31	3.82	1.53	--	--
147	2,000	RC-33	3C1ca	180	70	76.91	25.06	22.94	12.81	13.31	2.78	7.98	15.11	15.11	1.85	4.75	2.07	1.17	--	--
148	2,000	RC-33	3C2ca	+220	80	76.12	19.65	21.40	13.44	17.71	3.92	8.60	15.28	11.67	1.84	4.98	2.93	0.69	--	--
149	2,000	RC-8	A	8	20	49.64	12.29	13.46	10.61	--	--	20.32	--	--	--	--	--	--	8.85	21.19
150	2,000	RC-8	B2t	22	25	51.94	15.06	16.20	10.22	--	--	13.60	--	--	--	--	--	--	5.60	28.86
151	2,000	RC-8	2B3tca	72	50	62.14	14.23	17.66	14.00	--	--	13.77	--	--	--	--	--	--	5.00	19.09
152	2,000	RC-8	2K	112	60	78.18	6.06	12.58	18.98	--	--	17.60	--	--	--	--	--	--	2.11	2.11
153	2,000	RC-8	2Cca	+162	60	72.85	3.52	7.62	16.70	--	--	24.11	--	--	--	--	--	--	2.12	0.92
									Basin chronosequence											
154	7	RC-46A	Ap	20	0	23.03	0.05	0.05	0.72	--	--	48.81	--	--	1.50	--	--	--	8.03	20.13
155	7	RC-46A	ACca	40	0	56.25	0.00	0.05	2.28	--	--	35.53	--	--	1.60	--	--	--	3.52	4.70
156	7	RC-46A	2Cgca	70	0	26.30	0.00	0.05	0.64	--	--	44.33	--	--	1.70	--	--	--	8.54	20.83
157	7	RC-46A	2Cox	98	0	45.82	0.00	0.05	1.68	--	--	43.77	--	--	1.60	--	--	--	3.09	7.32
158	7	RC-46A	3Cn	+150	85	85.38	26.01	24.94	12.48	--	--	10.22	--	--	1.80	--	--	--	1.55	2.85
159	7	RC-46B	Apca	28	5	26.07	0.31	0.77	1.45	--	--	47.77	--	--	1.50	--	--	--	7.51	18.65
160	7	RC-46B	2Cca	60	30	55.39	5.39	6.11	5.08	--	--	34.11	--	--	1.60	--	--	--	3.32	7.18
161	7	RC-46B	3Cn	+150	85	85.38	26.01	24.94	12.48	--	--	10.22	--	--	1.80	--	--	--	1.55	2.85
162	20	RC-20	A	9	5	50.12	3.65	7.91	7.87	22.16	8.53	33.09	16.79	15.16	1.58	22.74	6.74	3.61	--	--
163	20	RC-20	2B1t	15	5	47.87	3.48	5.81	7.92	22.91	7.75	24.49	27.64	27.08	1.65	15.82	5.74	2.93	--	--
164	20	RC-20	2B2tca	32	35	65.05	17.51	15.15	9.04	18.28	5.07	14.02	20.93	20.91	1.75	9.08	3.63	1.31	--	--
165	20	RC-20	2B3tca	50	35	83.36	19.93	25.81	16.61	17.90	3.11	9.27	7.37	6.87	1.63	5.30	2.88	1.09	--	--
166	20	RC-20	3C1ca	130	75	89.60	16.80	17.73	21.97	29.51	3.60	5.25	5.15	5.12	1.85	3.34	1.53	0.37	--	--
167	20	RC-20	3C2ca	+330	85	94.34	15.40	33.99	20.24	21.26	3.45	3.43	2.23	2.23	1.80	2.35	0.35	0.73	--	--
168	20	RC-43	A	18	5	31.12	0.38	1.78	3.19	15.34	10.43	41.11	27.77	25.43	1.52	28.64	8.73	3.75	--	--
169	20	RC-43	B1t	33	5	44.29	3.44	8.01	5.88	15.45	11.52	38.24	17.47	14.94	1.52	26.81	8.24	3.18	--	--
170	20	RC-43	B2t	44	5	40.06	2.79	8.12	7.04	15.08	7.02	28.13	31.81	30.91	1.54	20.08	5.36	2.69	--	--
171	20	RC-43	2B3tca	65	65	71.33	15.76	22.72	12.69	15.41	4.74	17.02	11.65	10.89	1.49	11.91	3.89	1.22	--	--
172	20	RC-43	2C1ca	98	60	91.82	11.05	36.48	23.11	18.86	2.33	4.84	3.34	3.09	1.94	3.28	1.56	0.00	--	--
173	20	RC-43	3C2ca	+200	80	95.95	12.34	37.98	27.08	16.68	1.86	2.65	1.40	1.40	1.85	1.92	0.73	0.00	--	--
174	120	RC-27	A	6	5	39.14	0.35	0.67	2.55	--	--	36.07	--	--	1.45	--	--	--	10.34	14.45
175	120	RC-27	2B1t	11	55	45.39	4.74	3.16	4.19	--	--	30.50	--	--	1.42	--	--	--	6.89	17.22
176	120	RC-27	2B2t	19	65	37.51	7.74	4.10	2.88	--	--	20.79	--	--	1.41	--	--	--	6.32	35.38
177	120	RC-27	3B3ca	34	0	42.98	1.72	3.36	5.60	--	--	33.78	--	--	1.30	--	--	--	7.03	16.21
178	120	RC-27	3C1ca	74	0	42.10	0.45	2.55	0.74	--	--	34.44	--	--	1.60	--	--	--	5.55	17.91
179	120	RC-27	4C2ca	147	5	46.55	0.40	0.49	1.61	--	--	43.22	--	--	1.55	--	--	--	6.14	4.09
180	120	RC-27	5C3ca	+225	60	77.77	3.19	7.50	23.14	--	--	16.65	--	--	1.88	--	--	--	2.69	2.89

Supplementary table 2. Physical properties--Continued

No.	Age (ka)	Sample No.	Horizon	Basal depth (cm)	>2mm (%)	Percent of <2-mm fraction: Total sand	vco sand	co sand	med sand	fi sand	vfi sand	Total silt	<2μ clay	<1μ clay	Bulk density (g/cm^3)	percent of <2-mm fraction: co silt	med silt	vfi silt(2-.05μ)	co clay	fi clay (<0.5μ)
181	415	RC-23	A	3	5	29.12	5.40	4.77	2.61	8.27	8.08	52.52	18.36	16.10	1.24	38.49	10.60	3.43	--	--
182	415	RC-23	Bltca	7	25	38.28	8.18	6.02	3.05	9.61	11.41	45.98	15.74	13.03	1.51	33.54	9.07	3.38	--	--
183	415	RC-23	B2tca	14	40	36.93	7.68	6.59	3.94	11.00	7.73	40.34	22.73	19.82	1.50	30.94	7.19	2.20	--	--
184	415	RC-23	B3tca	29	35	56.72	20.78	12.54	6.03	11.23	6.13	27.91	15.37	14.08	1.55	21.59	5.11	1.22	--	--
185	415	RC-23	2K	60	55	80.31	32.05	19.96	9.57	14.36	4.38	13.05	6.64	5.82	1.64	9.69	2.34	1.02	--	--
186	415	RC-23	3Clca	121	85	64.23	13.83	16.93	10.49	16.97	6.01	20.68	15.09	12.00	1.80	10.91	5.56	4.20	--	--
187	415	RC-23	3C2ca	170	85	83.65	14.42	24.49	15.90	22.75	6.10	10.80	5.55	4.04	1.85	6.25	2.72	1.83	--	--
188	415	RC-23	4C3ca	226	50	74.51	14.50	30.85	14.02	11.88	3.26	18.95	6.54	4.93	1.83	13.42	4.17	1.36	--	--
199	415	RC-23	5C4ca	255	80	89.07	25.80	35.32	12.83	12.10	3.02	6.56	4.37	3.54	1.80	4.84	1.08	0.64	--	--
190	415	RC-23	5C5ca	310	80	84.98	22.48	26.89	12.48	17.89	5.24	11.49	3.53	3.31	1.80	8.10	1.85	1.54	--	--
191	415	RC-23	5C6ca	+320	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
192	600	RC-24	A	4	5	24.20	3.30	3.12	2.23	7.06	8.48	45.33	30.47	27.83	1.51	31.38	9.83	4.12	--	--
193	600	RC-24	Blt	9	10	22.11	2.88	2.78	2.06	6.60	7.80	43.83	34.06	31.69	1.69	30.28	10.58	2.96	--	--
194	600	RC-24	B2tca	19	5	17.74	1.34	1.66	1.36	5.44	7.94	45.06	37.20	33.90	1.40	32.31	9.88	2.87	--	--
195	600	RC-24	B3tca	30	5	22.56	2.35	2.15	1.77	7.26	9.03	51.40	26.04	22.80	1.28	35.67	11.97	3.75	--	--
196	600	RC-24	K	45	15	35.02	4.81	5.91	5.41	13.05	5.84	35.60	29.38	27.12	1.26	22.39	9.37	3.85	--	--
197	600	RC-24	2Clca	62	70	69.06	17.28	17.59	11.77	17.07	5.36	17.14	13.80	10.64	1.80	10.60	4.46	2.08	--	--
198	600	RC-24	2C2ca	87	80	88.54	14.57	25.82	20.24	22.98	4.93	8.42	3.04	2.32	1.80	5.07	2.53	0.81	--	--
199	600	RC-24	2C3ca	+300	80	97.40	4.05	37.14	34.78	19.95	1.47	2.10	0.50	0.29	1.80	0.94	1.17	0.00	--	--
200	945	RC-25	Aca	4	15	45.22	5.69	5.79	6.86	--	--	38.65	--	--	1.27	--	--	--	6.66	9.47
201	945	RC-25	Bltca	9	15	41.38	4.56	3.85	5.59	--	--	35.40	--	--	1.15	--	--	--	6.01	17.21
202	945	RC-25	B2tca	15	15	43.28	5.48	4.41	6.15	--	--	33.66	--	--	1.17	--	--	--	5.76	17.30
203	945	RC-25	B3tca	25	50	49.18	8.99	7.03	7.62	--	--	30.04	--	--	1.25	--	--	--	5.39	15.39
204	945	RC-25	2K	49	55	69.80	20.16	13.86	15.11	--	--	17.20	--	--	1.50	--	--	--	3.75	9.25
205	945	RC-25	2Clca	65	60	76.35	12.43	15.66	26.55	--	--	15.68	--	--	1.94	--	--	--	3.19	4.78
206	945	RC-25	2C2ca	91	75	86.58	12.13	16.47	33.72	--	--	10.24	--	--	1.85	--	--	--	1.38	1.80
207	945	RC-25	3C3ca	+130	20	74.46	12.47	10.66	19.83	--	--	18.88	--	--	1.78	--	--	--	3.40	3.26
208	945	RC-44	Aca	6	15	35.19	3.86	3.71	3.10	15.87	8.64	39.25	25.56	24.75	1.31	25.21	9.96	4.07	--	--
209	945	RC-44	Bltca	13	15	28.51	3.32	2.84	2.39	12.36	7.60	36.27	35.22	32.60	1.40	23.50	9.62	3.16	--	--
210	945	RC-44	B21tca	19	30	27.35	2.69	2.75	2.46	11.93	7.52	38.86	33.79	30.87	1.27	24.56	11.13	3.16	--	--
211	945	RC-44	B22tca	27	30	35.86	4.71	4.27	3.81	15.47	7.60	39.91	24.23	20.52	1.87	27.26	9.41	3.24	--	--
212	945	RC-44	2B31tca	45	55	40.17	9.06	7.15	4.83	13.74	5.39	37.19	22.64	19.05	1.33	27.02	7.75	2.42	--	--
213	945	RC-44	2B32tca	86	80	70.94	14.76	13.40	11.61	24.75	6.41	22.61	6.45	5.41	1.80	16.62	5.08	0.91	--	--
214	945	RC-44	2Cca	+120	85	85.47	10.87	15.53	19.54	33.04	6.49	12.46	2.07	1.96	1.80	9.90	2.57	0.00	--	--
215	2,000	RC-26A	A	6	20	45.57	14.00	9.55	4.75	11.13	6.14	42.59	11.84	8.55	1.57	28.39	10.44	3.76	--	--
216	2,000	RC-26A	Blt	11	25	38.78	10.55	7.99	4.67	9.89	5.68	35.49	25.73	22.06	1.55	23.39	9.26	2.83	--	--
217	2,000	RC-26A	B21t	20	5	36.31	9.37	7.40	4.46	9.57	5.51	37.23	26.46	22.99	1.55	25.88	8.60	2.74	--	--
218	2,000	RC-26A	B22tca	29	15	39.21	9.85	7.91	4.81	10.09	6.55	35.57	25.22	21.97	1.50	24.06	8.68	2.84	--	--
219	2,000	RC-26A	B3tca	40	15	42.85	10.48	9.45	5.63	11.35	5.94	32.07	25.08	20.94	1.26	19.06	10.62	2.38	--	--
220	2,000	RC-26A	2K	68	45	70.28	19.29	17.71	12.39	16.78	4.11	15.06	14.66	12.59	1.34	9.07	4.77	1.22	--	--
221	2,000	RC-26A	2Clca	145	75	82.21	19.90	24.23	14.13	19.36	4.59	13.78	4.01	3.25	1.89	7.64	3.87	2.28	--	--
222	2,000	RC-26A	2C2ca	247	65	91.36	30.12	35.93	12.94	10.44	1.93	6.20	2.44	1.83	1.98	3.15	1.59	1.45	--	--
223	2,000	RC-26A	3C3ca	295	60	94.06	24.24	50.00	12.51	6.26	1.06	4.18	1.76	1.65	1.94	2.29	0.30	1.59	--	--
224	2,000	RC-26B	A	5	5	55.43	10.35	11.22	9.11	--	--	30.49	--	--	1.45	--	--	--	5.31	8.77
225	2,000	RC-26B	Blt	10	15	44.19	6.53	7.57	7.85	--	--	29.05	--	--	1.46	--	--	--	5.79	20.97
226	2,000	RC-26B	B2tca	16	5	41.19	5.08	6.54	7.40	--	--	28.74	--	--	1.43	--	--	--	5.56	24.51
227	2,000	RC-26B	B31tca	25	5	44.45	7.20	7.88	7.77	--	--	29.88	--	--	1.30	--	--	--	5.02	20.65
228	2,000	RC-26B	B32tca	36	15	57.66	14.11	12.67	11.15	--	--	23.37	--	--	1.33	--	--	--	4.40	14.57
229	2,000	RC-26B	2K	48	45	76.51	21.95	19.38	17.87	--	--	12.96	--	--	1.54	--	--	--	2.97	7.56
230	2,000	RC-26B	2Clca	88	60	83.28	14.89	22.42	27.71	--	--	10.72	--	--	1.94	--	--	--	2.55	3.45
231	2,000	RC-26B	2C2ca	+170	70	91.33	2.41	9.69	32.05	--	--	7.64	--	--	1.88	--	--	--	0.25	0.78

Supplementary table 3. Extractive chemical analysis

[Analysts: M. C. Reheis and D. M. Cheney, U. S. Geological Survey. --, not measured]

Methods

Organic carbon content of most soils was measured by using the Walkley-Black titration procedure (Allison, 1965). Organic carbon by percent loss on ignition was measured on some soils that were analyzed by D. Cheney. $CaCO_3$ was measured with the Chittick apparatus (Bachman and Machette, 1977); 0 value indicates that $CaCO_3$ was not measured because no pedogenic $CaCO_3$ was present. Total $CaCO_3$ refers to the $CaCO_3$ content of the horizon including gravel and finer sediment.

Acid-soluble (Pa) and organic-bound (Po) phosphorus were measured in selected soil profiles with a spectrophotometer (Alexander and Robertson, 1970). Pa was extracted by shaking the samples in H_2SO_4 for 16 hours. Po was obtained by fusing samples with calcium acetate, burning off the organic matter, and shaking the samples in H_2SO_4 for 16 hours. To obtain an estimate of Po, the amount of Pa measured in the first extraction is subtracted from that measured in the second extraction (Williams and others, 1967).

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	Percent organic carbon	pH 1:1 H_2O	P (ppm)		Percent $CaCO_3$	
							organic	inorganic	<2 mm	total
1	modern	RC-R	channel gravel		0.16	6.8	0	277	0	0
2	modern	RC-M	channel gravel		0.96	8.0	0	269	0	0
				Mountain-front chronosequence						
3	7	RC-38	A1	9	2.87	6.3	193	312	0	0
4	7	RC-38	2A31	22	1.30	6.1	245	242	0	0
5	7	RC-38	2A32	33	1.16	6.0	178	184	0	0
6	7	RC-38	2AC	46	0.45	6.0	164	220	0	0
7	7	RC-38	3C1ox	85	0.15	6.3	37	178	0	0
8	7	RC-38	3C2ox	+120	0.26	5.9	0	121	0	0
9	20	RC-21	A	5	2.53	6.1	351	230	0	0
10	20	RC-21	B1t	12	2.45	6.3	245	198	0	0
11	20	RC-21	B2t	25	2.04	6.3	170	148	0	0
12	20	RC-21	2B3t	38	0.57	6.4	62	127	0	0
13	20	RC-21	3C1ox	73	0.17	6.6	63	202	0	0
14	20	RC-21	3C2ox	+110	0.15	6.8	13	194	0	0
15	20	RC-15	A	8	[1]8.94	6.0	--	--	0	0
16	20	RC-15	2B2t	23	[1]3.57	5.9	--	--	0	0
17	20	RC-15	2B3	43	[1]1.68	5.8	--	--	0	0
18	20	RC-15	2Cox	+68	[1]0.67	6.0	--	--	0	0
19	120	RC-31	A1	8	3.96	6.5	310	153	0	0
20	120	RC-31	A3	19	2.50	6.0	364	103	0	0
21	120	RC-31	B1t	32	1.97	6.1	167	136	0	0
22	120	RC-31	B21t	54	1.82	6.2	117	127	0	0
23	120	RC-31	B22t	81	1.27	6.3	142	100	0	0
24	120	RC-31	2B31t	123	0.15	6.6	39	77	0	0
25	120	RC-31	2B32t	145	0.05	6.8	175	130	0	0
26	120	RC-31	2Cox	+200	0.02	6.8	0	158	0	0
27	120	RC-17	A	9	[1]5.52	6.4	--	--	0	0
28	120	RC-17	B1t	20	[1]4.05	6.1	--	--	0	0
29	120	RC-17	B2t	31	[1]3.17	5.8	--	--	0	0
30	120	RC-17	B31t	50	[1]2.60	5.4	--	--	0	0
31	120	RC-17	2B32t	122	[1]1.42	5.7	--	--	0	0
32	120	RC-17	2Cox	+136	[1]0.96	5.1	--	--	0	0
33	415	RC-30	A1	9	4.98	6.2	303	168	0	0
34	415	RC-30	A3	17	2.71	6.1	283	114	0	0
35	415	RC-30	B1t	29	1.93	6.1	192	117	0	0
36	415	RC-30	B2t	53	1.42	6.2	153	89	0	0
37	415	RC-30	2B31t	81	1.17	6.4	100	84	0	0
38	415	RC-30	2B32t	170	0.10	6.7	0	279	0	0
39	415	RC-30	2Cox	+250	0.04	6.7	38	270	0	0

Supplementary table 3. Extractive chemical analysis--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	Percent organic carbon	pH 1:1 H_2O	P (ppm) organic	P (ppm) inorganic	Percent $CaCO_3$ <2 mm	Percent $CaCO_3$ total
40	600	RC-29	A1	9	2.90	6.2	287	208	0	0
41	600	RC-29	A3	18	1.93	5.9	223	133	0	0
42	600	RC-29	B1t	30	1.81	5.9	268	166	0	0
43	600	RC-29	B2t	50	1.66	6.0	120	175	0	0
44	600	RC-29	2B31t	79	1.52	5.9	123	166	0	0
45	600	RC-29	3B32t	167	0.00	6.7	86	236	0	0
46	600	RC-29	3Cox	+260	0.00	6.9	0	437	0	0
47	600	RC-16	A	27	[1]3.34	5.4	--	--	0	0
48	600	RC-16	B1t	47	[1]3.11	5.6	--	--	0	0
49	600	RC-16	2B2t	72	[1]2.44	5.6	--	--	0	0
50	600	RC-16	2B3t	127	[1]3.30	5.9	--	--	0	0
51	600	RC-16	2Cox	+197	[1]0.98	5.7	--	--	0	0
52	2,000	RC-28	A	7	3.12	6.0	--	--	0	0
53	2,000	RC-28	B1t	11	1.82	6.0	--	--	0	0
54	2,000	RC-28	B2t	17	2.16	6.0	--	--	0	0
55	2,000	RC-28	2B31t	47	0.56	6.0	--	--	0	0
56	2,000	RC-28	2B32t	141	0.19	6.6	--	--	0	0
57	2,000	RC-28	2Cox	+270	0.08	7.1	--	--	0	0
58	2,000	RC-14	A	17	[1]5.35	5.3	362	178	0	0
59	2,000	RC-14	B1t	32	[1]3.78	5.6	267	130	0	0
60	2,000	RC-14	B2t	44	[1]3.07	5.6	1130	115	0	0
61	2,000	RC-14	2B31t	84	[1]2.22	5.6	132	89	0	0
62	2,000	RC-14	3B32t	144	[1]1.43	6.2	146	129	0	0
63	2,000	RC-14	3Cox	+164	[1]0.85	6.3	0	132	0	0
					Transition chronosequence					
64	7	RC-40	A	13	[1]5.12	7.1	--	--	0	0
65	7	RC-40	Bs	46	[1]4.23	6.6	--	--	0	0
66	7	RC-40	2C1ox	65	[1]1.38	6.8	--	--	0	0
67	7	RC-40	2C2ox	310	[1]0.70	7.0	--	--	0	0
68	7	RC-42	A1	6	3.80	7.1	--	--	0	0
69	7	RC-42	A3	37	2.34	6.1	--	--	0	0
70	7	RC-42	2Bs	55	1.15	6.7	--	--	0	0
71	7	RC-42	3Bb	73	0.94	6.8	--	--	0	0
72	7	RC-42	3Coxb	+200	0.22	7.0	--	--	0	0
73	20	RC-22	A	5	3.54	6.9	--	--	0	0
74	20	RC-22	B1t	25	1.83	6.6	--	--	0	0
75	20	RC-22	B2t	43	1.37	6.8	--	--	0	0
76	20	RC-22	2B3t	57	0.73	6.9	--	--	0	0
77	20	RC-22	2C1ox	78	0.31	7.1	--	--	0	0
78	20	RC-22	2C2ox	175	0.14	6.9	--	--	0	0
79	20	RC-22	3Cca	197	0.55	7.9	--	--	3.01	--
80	20	RC-22	3Cn	+240	0.04	7.7	--	--	0	0
81	120	RC-12	A	9	[1]5.00	6.2	--	--	0	0
82	120	RC-12	B1t	17	[1]3.85	6.4	--	--	0	0
83	120	RC-12	B2t	39	[1]2.78	6.4	--	--	0	0
84	120	RC-12	2B3t	62	[1]1.90	6.8	--	--	0	0
85	120	RC-12	2Cox	+122	[1]1.06	7.0	--	--	0	0
86	120	RC-32	Ap	21	2.32	7.2	--	--	0	--
87	120	RC-32	2B2tca	37	1.54	7.5	--	--	0.58	--
88	120	RC-32	2B3tca	70	1.95	8.0	--	--	3.92	--
89	120	RC-32	3Cca	+80	0.07	8.1	--	--	0.38	--
90	120	RC-41	A	8	5.28	6.7	528	289	0	0
91	120	RC-41	B1t	17	2.17	6.6	266	169	0	0
92	120	RC-41	B2t	28	2.02	6.5	257	137	0	0
93	120	RC-41	2B31t	51	1.87	6.7	131	205	0	0
94	120	RC-41	2B32t	65	0.28	7.1	20	243	0	0
95	120	RC-41	2Cox	+100	0.06	7.3	48	188	0	0

Supplementary table 3. Extractive chemical analysis--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	Percent organic carbon	pH 1:1 H_2O	P (ppm) organic	P (ppm) inorganic	Percent $CaCO_3$ <2 mm	Percent $CaCO_3$ total
96	415	RC-11	A	9	[1]3.98	5.6	--	--	0	0
97	415	RC-11	B2t	20	[1]3.96	5.7	--	--	0	0
98	415	RC-11	B3t	50	[1]2.18	6.4	--	--	0	0
99	415	RC-11	2C1ca	100	[1]1.51	7.5	--	--	9.65	--
100	415	RC-11	2C2ca	+180	[1]0.56	7.7	--	--	1.31	--
101	415	RC-37	A	6	3.00	7.0	--	--	0	0
102	415	RC-37	B1t	18	1.83	7.1	--	--	0	0
103	415	RC-37	B2tca	45	1.92	7.3	--	--	0.2	--
104	415	RC-37	B3tca/K	63	2.22	7.7	--	--	43.8	--
105	415	RC-37	2C1ca	109	1.20	7.8	--	--	29.1	17.7
106	415	RC-37	3C2ca	230	0.01	8.1	--	--	1.29	4.1
107	415	RC-37	3C3ca	+240	--	--	--	--	--	--
108	600	RC-34	A1	8	2.05	5.7	--	--	0	0
109	600	RC-34	A3	14	2.47	5.4	--	--	0	0
110	600	RC-34	B1t	22	1.78	5.5	--	--	0	0
111	600	RC-34	B2t	37	1.56	5.5	--	--	0	0
112	600	RC-34	2B3t/ca	54	1.06	6.9	--	--	0.22	--
113	600	RC-34	3Cox/ca	89	0.26	6.7	--	--	7.34	5.8
114	600	RC-34	3C1ca	160	0.08	7.9	--	--	3.36	--
115	600	RC-34	3C2ca	+210	0.01	7.8	--	--	0.73	1.35
116	600	RC-35	A	5	[1]4.41	6.9	--	--	0	0
117	600	RC-35	B1t	10	[1]5.35	6.5	--	--	0	0
118	600	RC-35	B2tca	18	[1]6.84	7.0	--	--	3.4	--
119	600	RC-35	B3tca	32	[1]5.74	7.5	--	--	34.6	33.7
120	600	RC-35	2C1ca	54	[1]2.73	7.6	--	--	32.9	10.6
121	600	RC-35	2C2ca	135	[1]2.71	7.9	--	--	25.0	--
122	600	RC-35	2C3ca	225	[1]1.08	8.0	--	--	7.3	2.6
123	600	RC-35	2C4ca	+235	[1]1.02	8.0	--	--	4.8	--
124	945	RC-6	A	13	[1]5.58	6.6	--	--	0	0
125	945	RC-6	B1t	30	[1]3.30	6.6	--	--	0	0
126	945	RC-6	B2t	46	[1]3.43	6.8	--	--	0.3	--
127	945	RC-6	2C1ca	96	[1]2.42	7.5	--	--	31.5	--
128	945	RC-6	2C2ca	+126	[1]0.83	8.0	--	--	7.5	--
129	945	RC-36	A	7	0.23	7.3	--	--	0	0
130	945	RC-36	B1t	16	2.47	7.1	--	--	0	0
131	945	RC-36	B2tca	25	1.93	7.5	--	--	0.55	--
132	945	RC-36	B3tca	35	1.26	7.9	--	--	34.5	--
133	945	RC-36	K	53	1.16	8.0	--	--	53.2	49.1
134	945	RC-36	2C1ca	80	0.66	8.3	--	--	32.0	15.6
135	945	RC-36	3C2ca	103	1.46	8.3	--	--	20.2	--
136	945	RC-36	3C3ca	173	2.07	8.4	--	--	20.2	--
137	945	RC-36	3C4ca	200	1.18	8.5	--	--	7.47	--
138	945	RC-36	4C5ca	227	0.08	8.6	--	--	2.92	--
139	945	RC-36	4C6ca	+255	0.10	8.4	--	--	0.13	3.5
140	2,000	RC-33	A1	9	1.90	6.4	--	--	0	0
141	2,000	RC-33	A3	16	2.24	6.6	--	--	0	0
142	2,000	RC-33	B1t	24	2.23	6.6	--	--	0	0
143	2,000	RC-33	B2t	43	1.76	6.9	--	--	0	0
144	2,000	RC-33	2B3t/ca	58	2.00	7.6	--	--	4.63	--
145	2,000	RC-33	2K1	58	1.49	7.9	--	--	19.6	11.3
146	2,000	RC-33	2K2	92	0.32	7.9	--	--	17.1	10.0
147	2,000	RC-33	3C1ca	180	0.04	8.2	--	--	2.45	1.2
148	2,000	RC-33	3C2ca	+220	0.00	8.2	--	--	0.87	0.5
149	2,000	RC-8	A	8	[1]6.30	7.2	--	--	0	0
150	2,000	RC-8	B2t	22	[1]5.41	7.0	--	--	0	0
151	2,000	RC-8	2B3tca	72	[1]4.98	7.5	--	--	28.5	--
152	2,000	RC-8	2K	112	[1]2.16	7.8	--	--	22.3	--
153	2,000	RC-8	2Cca	+162	[1]1.66	7.8	--	--	16.7	--

Supplementary table 3. Extractive chemical analysis--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	Percent organic carbon	pH 1:1 H_2O	P (ppm) organic	P (ppm) inorganic	Percent $CaCO_3$ <2 mm	Percent $CaCO_3$ total
				Basin chronosequence						
154	7	RC-46A	Ap	20	1.78	8.0	--	--	1.49	1.49
155	7	RC-46A	ACca	40	0.37	8.1	--	--	5.58	5.58
156	7	RC-46A	2Cgca	70	1.06	8.1	--	--	3.06	3.06
157	7	RC-46A	2Cox	98	0.20	7.8	--	--	0.39	0.39
158	7	RC-46A	3Cn	+150	0.12	7.8	--	--	0.04	--
159	7	RC-46B	Apca	28	1.84	7.9	--	--	2.88	--
160	7	RC-46B	2Cca	60	0.40	8.0	--	--	2.71	--
161	7	RC-46B	3Cn	+150	0.12	7.8	--	--	0.04	--
162	20	RC-20	A	9	1.90	7.0	0	756	0	0
163	20	RC-20	2B1t	15	1.35	7.4	250	296	0	0
164	20	RC-20	2B2tca	32	0.72	7.7	289	287	0.35	1.2
165	20	RC-20	2B3tca	50	0.48	8.3	127	224	0.43	0.4
166	20	RC-20	3C1ca	130	0.07	8.6	25	364	0.99	3.3
167	20	RC-20	3C2ca	+330	0.02	8.9	7	278	0.28	--
168	20	RC-43	A	18	2.58	7.3	--	--	0	0
169	20	RC-43	B1t	33	2.07	7.7	--	--	0	0
170	20	RC-43	B2t	44	2.22	7.8	--	--	0	0
171	20	RC-43	2B3tca	65	0.90	8.1	--	--	7.92	--
172	20	RC-43	2C1ca	98	0.23	8.2	--	--	2.15	--
173	20	RC-43	3C2ca	+200	0.05	8.4	--	--	1.10	--
174	120	RC-27	A	6	[1]6.75	7.9	--	--	7.66	--
175	120	RC-27	2B1t	11	[1]7.69	7.5	--	--	1.17	--
176	120	RC-27	2B2t	19	[1]7.13	7.5	--	--	0.54	--
177	120	RC-27	3B3ca	34	[1]5.38	7.8	--	--	20.5	--
178	120	RC-27	3C1ca	74	[1]3.94	7.8	--	--	14.0	--
179	120	RC-27	4C2ca	147	[1]2.91	8.6	--	--	10.9	--
180	120	RC-27	5C3ca	+225	[1]1.20	7.9	--	--	6.50	--
181	415	RC-23	A	3	3.93	6.7	235	549	0	0
182	415	RC-23	B1tca	7	2.39	7.2	165	465	0.79	0.8
183	415	RC-23	B2tca	14	2.83	7.4	258	405	9.85	12.2
184	415	RC-23	B3tca	29	1.85	7.5	416	311	26.6	21.5
185	415	RC-23	2K	60	0.47	7.8	143	146	30.6	19.4
186	415	RC-23	3C1ca	121	0.19	7.8	81	150	6.39	--
187	415	RC-23	3C2ca	170	0.11	7.8	0	185	2.68	4.7
188	415	RC-23	4C3ca	226	0.04	8.0	--	--	7.66	1.3
189	415	RC-23	5C4ca	255	0.05	8.0	--	--	1.70	4.5
190	415	RC-23	5C5ca	310	0.10	8.0	--	--	7.30	1.3
191	415	RC-23	5C6ca	+320	--	--	--	--	--	--
192	600	RC-24	A	4	2.27	6.4	286	449	0	0
193	600	RC-24	B1t	9	2.36	6.7	187	378	0	0
194	600	RC-24	B2tca	19	1.60	7.4	291	446	1.53	--
195	600	RC-24	B3tca	30	1.34	8.0	350	383	25.6	--
196	600	RC-24	K	45	2.00	8.0	96	395	51.4	--
197	600	RC-24	2C1ca	62	0.32	8.3	122	203	16.4	4.3
198	600	RC-24	2C2ca	87	0.15	8.5	13	232	2.25	--
199	600	RC-24	2C3ca	+300	0.0	8.7	--	--	2.32	0.5
200	945	RC-25	Aca	4	[1]7.47	7.4	--	--	4.03	--
201	945	RC-25	B1tca	9	[1]8.42	7.3	--	--	18.4	--
202	945	RC-25	B2tca	15	[1]7.23	7.4	--	--	27.3	24.2
203	945	RC-25	B3tca	25	[1]6.52	7.4	--	--	36.0	23.0
204	945	RC-25	2K	49	[1]5.02	7.6	--	--	50.4	28.2
205	945	RC-25	2C1ca	65	[1]3.55	7.9	--	--	30.4	15.5
206	945	RC-25	2C2ca	91	[1]2.10	8.1	--	--	11.0	--
207	945	RC-25	3C3ca	+130	[1]3.30	8.4	--	--	11.2	--
208	945	RC-44	Aca	6	2.49	7.5	211	452	3.31	--
209	945	RC-44	B1tca	13	2.67	7.5	273	384	5.88	--
210	945	RC-44	B21tca	19	2.72	7.8	295	450	16.1	--
211	945	RC-44	B22tca	27	2.43	7.9	281	389	28.7	--
212	945	RC-44	B31tca	45	1.91	7.9	270	401	44.5	--
213	945	RC-44	2B32tca	86	0.45	8.3	76	205	11.9	--
214	945	RC-44	2Cca	+120	0.21	8.6	32	235	2.84	--

Supplementary table 3. Extractive chemical analysis--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	Percent organic carbon	pH 1:1 H_2O	P (ppm) organic	P (ppm) inorganic	Percent $CaCO_3$ <2 mm	Percent $CaCO_3$ total
215	2,000	RC-26A	A	6	1.82	6.6	153	385	0	0
216	2,000	RC-26A	B1t	11	2.30	6.9	164	322	0	0
217	2,000	RC-26A	B21t	20	2.12	7.0	207	331	0	0
218	2,000	RC-26A	B22tca	29	2.29	7.4	161	341	1.05	--
219	2,000	RC-26A	B3tca	40	2.08	7.9	329	320	30.8	--
220	2,000	RC-26A	2K	68	1.78	7.9	300	234	50.7	28.5
221	2,000	RC-26A	2C1ca	145	0.17	8.9	78	318	15.4	4.1
222	2,000	RC-26A	2C2ca	247	0.02	8.9	0	229	2.99	0.7
223	2,000	RC-26A	3C3ca	295	0.02	8.6	66	156	0.37	--
224	2,000	RC-26B	A	5	[1]5.86	6.8	--	--	0	0
225	2,000	RC-26B	B1t	10	[1]6.34	6.8	--	--	0	0
226	2,000	RC-26B	B2tca	16	[1]6.30	7.1	--	--	0.82	--
227	2,000	RC-26B	B31tca	25	[1]7.69	7.4	--	--	20.2	--
228	2,000	RC-26B	B32tca	36	[1]6.66	7.5	--	--	37.0	--
229	2,000	RC-26B	2K	48	[1]6.12	7.6	--	--	41.7	25.5
230	2,000	RC-26B	2C1ca	88	[1]3.34	7.9	--	--	29.5	--
231	2,000	RC-26B	2C2ca	+170	[1]1.58	8.2	--	--	9.22	--

[1]Measured by loss on ignition.

Supplementary table 4. Clay mineralogy

[Analyst: M. C. Reheis, U. S. Geological Survey. --, not measured]

Methods

Samples of clay fractions drawn from settling tubes after particle-size analyses were plated on ceramic tiles (Whittig, 1965). X-ray-diffraction traces (CuK alpha radiation) were run on these oriented clays after the following treatments: air-dried, glycolated, and heated to 400 and 550 °C. Clay mineral percentage for Rock Creek soils was calculated by using the formulas based on peak heights and areas developed by Schultz (1964) in work on the mineralogy of the Pierre Shale (Upper Cretaceous). In his study, these formulas gave an accuracy of determination of ±10 percent when clay constituted more than 15 percent of the sample (the rest was amorphous material and/ or nonclay minerals).

No.	Age (ka)	Sample number	Horizon	Basal depth	Percent of clay mineral: Kaolinite	Chlorite	Vermiculite	Mica	Mixed-layer smectite-illite	Smectite
1	modern	RC-R	channel gravel		45	9	0	8	24	14
2	modern	RC-M	channel gravel		--	--	--	--	--	--
			Mountain-front chronosequence							
3	7	RC-38	A1	9	27	11	0	42	12	7
4	7	RC-38	2A31	22	20	10	0	42	19	9
5	7	RC-38	2A32	33	19	2	0	18	51	9
6	7	RC-38	2AC	46	10	3	0	18	61	9
7	7	RC-38	3C1ox	85	6	2	0	21	66	5
8	7	RC-38	3C2ox	+120	--	--	--	--	--	--
9	20	RC-21	A	5	13	3	0	17	61	6
10	20	RC-21	B1t	12	27	4	0	31	26	12
11	20	RC-21	B2t	25	25	2	0	25	33	15
12	20	RC-21	2B3t	38	23	2	15	12	20	28
13	20	RC-21	3C1ox	73	8	2	0	14	72	4
14	20	RC-21	3C2ox	+110	--	--	--	--	--	--

Supplementary table 4. Clay mineralogy--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth	percent of clay mineral Kaoli-nite	Chlo-rite	Vermi-culite	Mica	Mixed-layer smectite-illite	Smec-tite
15	20	RC-15	A	8	--	--	--	--	--	--
16	20	RC-15	2B2t	23	--	--	--	--	--	--
17	20	RC-15	2B3	43	--	--	--	--	--	--
18	20	RC-15	2Cox	+68	--	--	--	--	--	--
19	120	RC-31	A1	8	26	6	0	39	25	4
20	120	RC-31	A3	19	22	4	0	44	23	8
21	120	RC-31	B1t	32	27	3	0	19	35	15
22	120	RC-31	B21t	54	22	9	7	21	16	26
23	120	RC-31	B22t	81	11	4	8	22	46	9
24	120	RC-31	2B31t	123	8	6	12	17	51	7
25	120	RC-31	2B32t	145	3	2	15	10	59	11
26	120	RC-31	2Cox	+200	1	5	24	24	36	10
27	120	RC-17	A	9	--	--	--	--	--	--
28	120	RC-17	B1t	20	--	--	--	--	--	--
29	120	RC-17	B2t	31	--	--	--	--	--	--
30	120	RC-17	B31t	50	--	--	--	--	--	--
31	120	RC-17	2B32t	122	--	--	--	--	--	--
32	120	RC-17	2Cox	+136	--	--	--	--	--	--
33	415	RC-30	A1	9	8	10	0	72	2	8
34	415	RC-30	A3	17	17	9	0	75	0	5
35	415	RC-30	B1t	29	15	2	3	52	21	7
36	415	RC-30	B2t	53	2	2	4	15	65	12
37	415	RC-30	2B31t	81	4	2	10	10	64	11
38	415	RC-30	2B32t	170	4	2	5	23	56	10
39	415	RC-30	2Cox	+250	1	2	2	11	73	10
40	600	RC-29	A1	9	22	3	0	40	23	12
41	600	RC-29	A3	18	15	3	0	54	18	10
42	600	RC-29	B1t	30	26	2	5	40	16	11
43	600	RC-29	B2t	50	23	6	10	38	6	17
44	600	RC-29	2B31t	79	13	3	6	50	16	12
45	600	RC-29	3B32t	167	3	2	8	19	51	17
46	600	RC-29	3Cox	+260	3	1	8	20	50	17
47	600	RC-16	A	27	--	--	--	--	--	--
48	600	RC-16	B1t	47	--	--	--	--	--	--
49	600	RC-16	2B2t	72	--	--	--	--	--	--
50	600	RC-16	2B3t	127	--	--	--	--	--	--
51	600	RC-16	2Cox	+197	--	--	--	--	--	--
52	2,000	RC-28	A	7	--	--	--	--	--	--
53	2,000	RC-28	B1t	11	--	--	--	--	--	--
54	2,000	RC-28	B2t	17	--	--	--	--	--	--
55	2,000	RC-28	2B31t	47	--	--	--	--	--	--
56	2,000	RC-28	2B32t	141	--	--	--	--	--	--
57	2,000	RC-28	2Cox	+270	--	--	--	--	--	--
58	2,000	RC-14	A	17	13	0	0	47	41	0
59	2,000	RC-14	B1t	32	15	0	0	26	54	5
60	2,000	RC-14	B2t	44	24	0	0	15	53	8
61	2,000	RC-14	2B31t	84	10	0	9	44	26	12
62	2,000	RC-14	3B32t	144	1	0	21	5	53	20
63	2,000	RC-14	3Cox	+164	4	0	17	15	53	11
				Transition chronosequence						
64	7	RC-40	A	13	--	--	--	--	--	--
65	7	RC-40	Bs	46	--	--	--	--	--	--
66	7	RC-40	2C1ox	65	--	--	--	--	--	--
67	7	RC-40	2C2ox	310	--	--	--	--	--	--
68	7	RC-42	A1	6	31	7	0	31	20	11
69	7	RC-42	A3	37	28	6	0	36	19	11
70	7	RC-42	2Bs	55	37	5	0	42	0	17
71	7	RC-42	3Bb	73	39	5	0	38	0	18
72	7	RC-42	3Coxb	+200	42	0	0	29	3	26

Supplementary table 4. Clay mineralogy--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth	Kaolinite	Chlorite	Vermiculite	Mica	Mixed-layer smectite-illite	Smectite
					percent of clay mineral					
73	20	RC-22	A	5	27	5	0	45	15	7
74	20	RC-22	B1t	25	20	6	0	37	31	6
75	20	RC-22	B2t	43	18	0	0	25	52	6
76	20	RC-22	2B3t	57	13	6	0	47	15	19
77	20	RC-22	2C1ox	78	15	7	0	31	27	20
78	20	RC-22	2C2ox	175	20	0	0	24	37	19
79	20	RC-22	3Cca	197	--	--	--	--	--	--
80	20	RC-22	3Cn	+240	--	--	--	--	--	--
81	120	RC-12	A	9	--	--	--	--	--	--
82	120	RC-12	B1t	17	--	--	--	--	--	--
83	120	RC-12	B2t	39	--	--	--	--	--	--
84	120	RC-12	2B3t	62	--	--	--	--	--	--
85	120	RC-12	2Cox	+122	--	--	--	--	--	--
86	120	RC-32	Ap	21	14	4	0	12	50	20
87	120	RC-32	2B2tca	37	23	3	0	20	37	16
88	120	RC-32	2B3tca	70	32	5	0	22	19	22
89	120	RC-32	3Cca	+80	32	4	4	18	30	11
90	120	RC-41	A	8	56	0	0	33	3	8
91	120	RC-41	B1t	17	49	2	0	19	21	9
92	120	RC-41	B2t	28	40	1	0	11	39	9
93	120	RC-41	2B31t	51	38	2	0	8	43	10
94	120	RC-41	2B32t	65	37	4	0	13	34	13
95	120	RC-41	2Cox	+100	24	2	0	9	56	9
96	415	RC-11	A	9	--	--	--	--	--	--
97	415	RC-11	B2t	20	--	--	--	--	--	--
98	415	RC-11	B3t	50	--	--	--	--	--	--
99	415	RC-11	2C1ca	100	--	--	--	--	--	--
100	415	RC-11	2C2ca	+180	--	--	--	--	--	--
101	415	RC-37	A	6	21	4	0	38	33	5
102	415	RC-37	B1t	18	23	3	0	16	47	11
103	415	RC-37	B2tca	45	27	3	5	16	26	23
104	415	RC-37	B3tca/K	63	24	3	4	13	26	31
105	415	RC-37	2C1ca	109	19	6	0	17	27	31
106	415	RC-37	3C2ca	230	28	5	0	23	11	33
107	415	RC-37	3C3ca	+240	--	--	--	--	--	--
108	600	RC-34	A1	8	21	0	0	30	40	8
109	600	RC-34	A3	14	26	6	0	32	24	12
110	600	RC-34	B1t	22	15	7	0	31	40	7
111	600	RC-34	B2t	37	14	2	5	46	19	14
112	600	RC-34	2B3t/ca	54	11	5	0	23	39	22
113	600	RC-34	3Cox/ca	89	19	6	14	22	19	19
114	600	RC-34	3C1ca	160	29	7	0	18	17	30
115	600	RC-34	3C2ca	+210	--	--	--	--	--	--
116	600	RC-35	A	5	--	--	--	--	--	--
117	600	RC-35	B1t	10	--	--	--	--	--	--
118	600	RC-35	B2tca	18	--	--	--	--	--	--
119	600	RC-35	B3tca	32	--	--	--	--	--	--
120	600	RC-35	2C1ca	54	--	--	--	--	--	--
121	600	RC-35	2C2ca	135	--	--	--	--	--	--
122	600	RC-35	2C3ca	225	--	--	--	--	--	--
123	600	RC-35	2C4ca	+235	--	--	--	--	--	--
124	945	RC-6	A	13	--	--	--	--	--	--
125	945	RC-6	B1t	30	--	--	--	--	--	--
126	945	RC-6	B2t	46	--	--	--	--	--	--
127	945	RC-6	2C1ca	96	--	--	--	--	--	--
128	945	RC-6	2C2ca	+126	--	--	--	--	--	--

Supplementary table 4. Clay mineralogy--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth	Kaolinite	Chlorite	Vermiculite	Mica	Mixed-layer smectite-illite	Smectite
					percent of clay mineral					
129	945	RC-36	A	7	46	5	0	33	2	15
130	945	RC-36	B1t	16	26	1	0	26	39	9
131	945	RC-36	B2tca	25	20	7	8	18	17	30
132	945	RC-36	B3tca	35	37	6	13	20	10	14
133	945	RC-36	K	53	34	6	18	15	2	24
134	945	RC-36	2C1ca	80	35	4	5	20	15	22
135	945	RC-36	3C2ca	103	31	5	17	20	0	37
136	945	RC-36	3C3ca	173	--	--	--	--	--	--
137	945	RC-36	3C4ca	200	34	6	0	20	0	40
138	945	RC-36	4C5ca	227	--	--	--	--	--	--
139	945	RC-36	4C6ca	+255	31	3	0	24	0	42
140	2,000	RC-33	A1	9	27	8	0	24	32	8
141	2,000	RC-33	A3	16	28	5	0	31	18	18
142	2,000	RC-33	B1t	24	13	2	0	15	59	10
143	2,000	RC-33	B2t	43	25	2	0	22	33	19
144	2,000	RC-33	2B3t/ca	58	13	0	0	13	63	11
145	2,000	RC-33	2K1	58	--	--	--	--	--	--
146	2,000	RC-33	2K2	92	10	0	0	11	43	36
147	2,000	RC-33	3C1ca	180	7	0	0	4	65	23
148	2,000	RC-33	3C2ca	+220	6	0	0	7	66	21
149	2,000	RC-8	A	8	--	--	--	--	--	--
150	2,000	RC-8	B2t	22	--	--	--	--	--	--
151	2,000	RC-8	2B3tca	72	--	--	--	--	--	--
152	2,000	RC-8	2K	112	--	--	--	--	--	--
153	2,000	RC-8	2Cca	+162	--	--	--	--	--	--
				Basin chronosequence						
154	7	RC-46A	Ap	20	--	--	--	--	--	--
155	7	RC-46A	ACca	40	--	--	--	--	--	--
156	7	RC-46A	2Cgca	70	--	--	--	--	--	--
157	7	RC-46A	2Cox	98	--	--	--	--	--	--
158	7	RC-46A	3Cn	+150	--	--	--	--	--	--
159	7	RC-46B	Apca	28	--	--	--	--	--	--
160	7	RC-46B	2Cca	60	--	--	--	--	--	--
161	7	RC-46B	3Cn	+150	--	--	--	--	--	--
162	20	RC-20	A	9	33	0	0	31	23	13
163	20	RC-20	2B1t	15	21	0	0	13	52	14
164	20	RC-20	2B2tca	32	33	0	0	16	23	28
165	20	RC-20	2B3tca	50	35	1	0	19	15	29
166	20	RC-20	3C1ca	130	32	0	0	18	12	38
167	20	RC-20	3C2ca	+330	--	--	--	--	--	--
168	20	RC-43	A	18	--	--	--	--	--	--
169	20	RC-43	B1t	33	--	--	--	--	--	--
170	20	RC-43	B2t	44	--	--	--	--	--	--
171	20	RC-43	2B3tca	65	--	--	--	--	--	--
172	20	RC-43	2C1ca	98	--	--	--	--	--	--
173	20	RC-43	3C2ca	+200	--	--	--	--	--	--
174	120	RC-27	A	6	--	--	--	--	--	--
175	120	RC-27	2B1t	11	--	--	--	--	--	--
176	120	RC-27	2B2t	19	--	--	--	--	--	--
177	120	RC-27	2B3ca	34	--	--	--	--	--	--
178	120	RC-27	3C1ca	74	--	--	--	--	--	--
179	120	RC-27	4C2ca	147	--	--	--	--	--	--
180	120	RC-27	5C3ca	+225	--	--	--	--	--	--
181	415	RC-23	A	3	21	0	0	14	55	10
182	415	RC-23	B1tca	7	19	2	0	23	42	13
183	415	RC-23	B2tca	14	22	1	0	22	33	22
184	415	RC-23	B3tca	29	33	2	0	7	38	20
185	415	RC-23	2K	60	27	1	0	6	25	41
186	415	RC-23	3C1ca	121	21	0	0	8	29	43
187	415	RC-23	3C2ca	170	21	0	0	6	24	48
188	415	RC-23	4C3ca	226	--	--	--	--	--	--
189	415	RC-23	5C4ca	255	--	--	--	--	--	--
190	415	RC-23	5C5ca	310	--	--	--	--	--	--
191	415	RC-23	5C6ca	+320	--	--	--	--	--	--

Supplementary table 4. Clay mineralogy--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth	Kaoli-nite	Chlo-rite	Vermi-culite	Mica	Mixed-layer smectite-illite	Smec-tite
					percent of clay mineral					
192	600	RC-24	A	4	12	2	0	20	54	13
193	600	RC-24	Blt	9	20	2	0	19	45	13
194	600	RC-24	B2tca	19	19	1	0	30	36	14
195	600	RC-24	B3tca	30	32	2	0	19	25	22
196	600	RC-24	K	45	23	2	0	12	30	32
197	600	RC-24	2Clca	62	18	1	0	4	32	44
198	600	RC-24	2C2ca	87	--	--	--	--	--	--
199	600	RC-24	2C3ca	+300	--	--	--	--	--	--
200	945	RC-25	Aca	4	--	--	--	--	--	--
201	945	RC-25	Bltca	9	--	--	--	--	--	--
202	945	RC-25	B2tca	15	--	--	--	--	--	--
203	945	RC-25	B3tca	25	--	--	--	--	--	--
204	945	RC-25	2K	49	--	--	--	--	--	--
205	945	RC-25	2Clca	65	--	--	--	--	--	--
206	945	RC-25	2C2ca	91	--	--	--	--	--	--
207	945	RC-25	3C3ca	+130	--	--	--	--	--	--
208	945	RC-44	Aca	6	35	9	0	33	9	14
209	945	RC-44	Bltca	13	19	5	0	10	59	8
210	945	RC-44	B21tca	19	25	3	0	21	36	14
211	945	RC-44	B22tca	27	7	4	0	15	44	30
212	945	RC-44	B31tca	45	35	5	0	16	12	32
213	945	RC-44	2B32tca	86	12	2	0	4	32	51
214	945	RC-44	2Cca	+120	3	2	0	3	39	53
215	2,000	RC-26A	A	6	18	9	0	37	26	11
216	2,000	RC-26A	Blt	11	24	2	0	10	52	12
217	2,000	RC-26A	B21t	20	16	2	0	15	42	25
218	2,000	RC-26A	B22tca	29	12	8	0	32	11	37
219	2,000	RC-26A	B3tca	40	--	--	--	--	--	--
220	2,000	RC-26A	2K	68	2	1	0	4	45	49
221	2,000	RC-26A	2Clca	145	2	0	0	2	46	50
222	2,000	RC-26A	2C2ca	247	--	--	--	--	--	--
223	2,000	RC-26A	3C3ca	295	--	--	--	--	--	--
224	2,000	RC-26B	A	5	--	--	--	--	--	--
225	2,000	RC-26B	Blt	10	--	--	--	--	--	--
226	2,000	RC-26B	B2tca	16	--	--	--	--	--	--
227	2,000	RC-26B	B31tca	25	--	--	--	--	--	--
228	2,000	RC-26B	B32tca	36	--	--	--	--	--	--
229	2,000	RC-26B	2K	48	--	--	--	--	--	--
230	2,000	RC-26B	2Clca	88	--	--	--	--	--	--
231	2,000	RC-26B	2C2ca	+170	--	--	--	--	--	--

Supplementary table 5. Total chemical analysis of fine fraction by induction-coupled plasma spectroscopy

[Analysts: C. Gent and D. Fey under supervision of J. L. Seeley and L. R. Layman, U.S. Geological Survey. --, not measured]

Methods

The less-than-2 mm and the silt-plus-clay fractions of selected soil samples and the dust-trap sample were analyzed for major elements and Zr by the Analytical Laboratories of the U. S. Geological Survey. To avoid chemical contamination in obtaining the silt-plus-clay fraction, soils were dispersed by shaking samples overnight in distilled water and then sonicating them in a water bath. Sand was removed by wet-sieving, and the silt-plus-clay fraction was dried and ground.

Oxides were determined by inductively coupled argon plasma emission spectroscopy (ICP). This method is noted for its high sensitivity to most elements once they are in solution (Taggart and others, 1981) (ICP accuracy is estimated at 3-5 percent and precision at 1-2 percent; J. E. Taggart, oral commun., 1982). X-ray fluorescence (XRF) is a more accurate method, but it is not sensitive to small amounts of such elements as Zr (there is less than 0.1 percent in the silt-plus-clay fractions of soils in the study area). Because determination of Zr was critical to this study, all samples were run using ICP, with revised pretreatments that dissolved Zr. Selected samples were split and analyzed by using both ICP and XRF as a check on the accuracy of ICP, and the separate analyses agreed closely (data not shown).

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	Percent of silt-plus-clay fraction									
					SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	ZrO_2
1	modern	RC-R	channel gravel		51	14.37	7.10	2.90	3.48	2.57	2.01	0.73	0.092	0.064
2	modern	RC-M	channel gravel		67	12.16	3.96	1.63	2.56	1.35	2.17	0.57	0.061	0.082
Mountain-front chronosequence														
3	7	RC-38	A1	9	56	12.57	3.79	1.39	2.11	2.79	2.22	0.47	0.084	0.043
4	7	RC-38	2A31	22	58	13.55	4.03	1.43	1.97	2.99	2.29	0.48	0.085	0.046
5	7	RC-38	2A32	33	60	14.05	4.06	1.44	2.04	3.22	2.28	0.50	0.078	0.047
6	7	RC-38	2AC	46	62	14.74	3.94	1.48	2.27	3.69	2.33	0.48	0.056	0.050
7	7	RC-38	3C1ox	85	64	15.43	3.73	1.54	2.03	4.22	2.45	0.47	0.039	0.046
8	7	RC-38	3C2ox	+120	67	16.45	4.43	1.77	2.08	4.16	2.53	0.57	0.038	0.053
9	20	RC-21	A	5	60	13.21	4.52	1.21	1.47	1.59	2.28	0.60	0.079	0.045
10	20	RC-21	B1t	12	62	14.33	4.85	1.21	1.08	1.52	2.35	0.63	0.073	0.047
11	20	RC-21	B2t	25	62	14.78	4.98	1.30	1.00	1.37	2.28	0.63	0.053	0.043
12	20	RC-21	2B3t	38	62	15.52	5.15	1.43	1.16	1.36	2.10	0.58	0.039	0.043
13	20	RC-21	3C1ox	73	58	16.31	6.41	1.74	1.93	2.60	2.18	0.65	0.059	0.076
14	20	RC-21	3C2ox	+110	64	16.86	5.48	1.66	2.39	3.68	2.41	0.57	0.052	0.079
15	20	RC-15	A	8	--	--	--	--	--	--	--	--	--	--
16	20	RC-15	2B2t	23	62	13.14	4.23	1.51	1.86	2.10	2.20	0.57	0.085	0.050
17	20	RC-15	2B3	43	--	--	--	--	--	--	--	--	--	--
18	20	RC-15	2Cox	+68	--	--	--	--	--	--	--	--	--	--
19	120	RC-31	A1	8	59	13.48	4.65	1.29	1.65	1.59	2.41	0.58	0.093	0.045
20	120	RC-31	A3	19	58	14.23	4.94	1.31	1.44	1.60	2.34	0.57	0.065	0.042
21	120	RC-31	B1t	32	60	14.61	4.76	1.28	1.17	1.64	2.25	0.55	0.040	0.041
22	120	RC-31	B21t	54	62	14.90	4.97	1.45	1.25	1.66	2.18	0.57	0.036	0.046
23	120	RC-31	B22t	81	52	19.85	6.63	1.66	1.54	1.63	1.75	0.60	0.036	0.036
24	120	RC-31	2B31t	123	52	20.04	6.94	1.92	2.14	2.48	1.78	0.68	0.054	0.039
25	120	RC-31	2B32t	145	51	19.09	8.47	2.69	2.56	2.35	1.54	0.78	0.071	0.032
26	120	RC-31	2Cox	+200	53	18.41	7.94	2.72	2.60	2.63	1.82	0.83	0.075	0.046
27	120	RC-17	A	9	--	--	--	--	--	--	--	--	--	--
28	120	RC-17	B1t	20	--	--	--	--	--	--	--	--	--	--
29	120	RC-17	B2t	31	64	15.44	4.85	1.46	0.99	1.25	2.27	0.63	0.041	0.051
30	120	RC-17	B31t	50	--	--	--	--	--	--	--	--	--	--
31	120	RC-17	2B32t	122	--	--	--	--	--	--	--	--	--	--
32	120	RC-17	2Cox	+136	--	--	--	--	--	--	--	--	--	--
33	415	RC-30	A1	9	56	13.52	4.99	1.49	1.90	1.64	2.41	0.60	0.090	0.041
34	415	RC-30	A3	17	53	14.59	5.59	1.59	1.65	1.58	2.28	0.60	0.074	0.036
35	415	RC-30	B1t	29	56	15.50	5.84	1.71	1.61	1.62	2.30	0.62	0.062	0.038
36	415	RC-30	B2t	53	48	18.56	8.08	2.55	1.99	1.61	1.84	0.71	0.053	0.028
37	415	RC-30	2B31t	81	49	18.49	7.74	2.64	1.75	1.44	1.71	0.60	0.054	0.026
38	415	RC-30	2B32t	170	47	19.66	9.14	2.82	1.79	1.29	1.65	0.65	0.076	0.030
39	415	RC-30	2Cox	+250	49	19.85	9.28	2.99	1.59	1.19	2.00	0.63	0.065	0.026

Supplementary table 5. Total chemical analysis of fine fraction by induction-coupled plasma spectroscopy--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	Percent of silt-plus-clay fraction									
					SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	ZrO_2
40	600	RC-29	A1	9	59	14.46	5.49	1.72	1.75	1.81	2.53	0.65	0.074	0.040
41	600	RC-29	A3	18	56	14.93	5.68	1.64	1.71	1.79	2.46	0.67	0.085	0.036
42	600	RC-29	B1t	30	58	14.86	5.52	1.61	1.65	1.85	2.29	0.68	0.070	0.038
43	600	RC-29	B2t	50	55	15.73	6.31	2.36	1.62	1.72	2.11	0.66	0.063	0.032
44	600	RC-29	2B31t	79	56	15.80	6.68	2.06	1.85	1.87	2.24	0.72	0.085	0.040
45	600	RC-29	3B32t	167	53	16.39	8.50	3.23	2.57	2.32	2.02	0.85	0.087	0.036
46	600	RC-29	3Cox	+260	51	18.05	8.71	3.22	1.87	1.44	1.99	0.65	0.063	0.026
47	600	RC-16	A	27	--	--	--	--	--	--	--	--	--	--
48	600	RC-16	B1t	47	--	--	--	--	--	--	--	--	--	--
49	600	RC-16	2B2t	72	53	18.13	7.42	2.77	1.94	1.60	1.75	0.65	0.053	0.039
50	600	RC-16	2B3t	127	--	--	--	--	--	--	--	--	--	--
51	600	RC-16	2Cox	+197	--	--	--	--	--	--	--	--	--	--
52	2,000	RC-28	A	7	--	--	--	--	--	--	--	--	--	--
53	2,000	RC-28	B1t	11	--	--	--	--	--	--	--	--	--	--
54	2,000	RC-28	B2t	17	53	17.16	5.71	1.67	1.51	1.90	2.43	0.58	0.061	0.036
55	2,000	RC-28	2B31t	47	--	--	--	--	--	--	--	--	--	--
56	2,000	RC-28	2B32t	141	--	--	--	--	--	--	--	--	--	--
57	2,000	RC-28	2Cox	+270	--	--	--	--	--	--	--	--	--	--
58	2,000	RC-14	A	17	60	13.33	4.41	1.09	1.31	1.43	2.37	0.63	0.075	0.035
59	2,000	RC-14	B1t	32	60	14.90	4.78	1.21	1.06	1.31	2.31	0.65	0.050	0.039
60	2,000	RC-14	B2t	44	59	16.27	5.42	1.49	1.18	1.25	2.06	0.64	0.045	0.032
61	2,000	RC-14	2B31t	84	53	17.96	6.31	1.86	1.71	2.10	1.84	0.65	0.056	0.030
62	2,000	RC-14	2B32t	144	49	18.70	7.80	2.59	1.93	1.82	1.69	0.62	0.076	0.022
63	2,000	RC-14	3Cox	+164	53	18.41	6.88	2.04	1.94	2.37	2.43	0.65	0.078	0.038
					Transition chronosequence									
64	7	RC-40	A	13	--	--	--	--	--	--	--	--	--	--
65	7	RC-40	Bs	46	--	--	--	--	--	--	--	--	--	--
66	7	RC-40	2C1ox	65	--	--	--	--	--	--	--	--	--	--
67	7	RC-40	2C2ox	310	--	--	--	--	--	--	--	--	--	--
68	7	RC-42	A1	6	64	10.89	3.51	1.13	1.34	1.58	2.46	0.50	0.057	0.053
69	7	RC-42	A3	37	64	11.87	3.95	1.23	1.37	1.50	2.37	0.53	0.061	0.050
70	7	RC-42	2Bs	55	64	13.16	4.35	1.38	1.30	1.47	2.30	0.57	0.047	0.051
71	7	RC-42	3Bb	73	64	13.17	4.56	1.44	1.37	1.62	2.34	0.57	0.057	0.052
72	7	RC-42	3Coxb	+200	60	15.16	5.74	1.74	1.61	1.63	2.34	0.57	0.062	0.053
73	20	RC-22	A	5	--	--	--	--	--	--	--	--	--	--
74	20	RC-22	B1t	25	--	--	--	--	--	--	--	--	--	--
75	20	RC-22	B2t	43	--	--	--	--	--	--	--	--	--	--
76	20	RC-22	2B3t	57	--	--	--	--	--	--	--	--	--	--
77	20	RC-22	2C1ox	78	--	--	--	--	--	--	--	--	--	--
78	20	RC-22	2C2ox	175	--	--	--	--	--	--	--	--	--	--
79	20	RC-22	3Cca	197	--	--	--	--	--	--	--	--	--	--
80	20	RC-22	3Cn	+240	--	--	--	--	--	--	--	--	--	--
81	120	RC-12	A	9	--	--	--	--	--	--	--	--	--	--
82	120	RC-12	B1t	17	--	--	--	--	--	--	--	--	--	--
83	120	RC-12	B2t	39	--	--	--	--	--	--	--	--	--	--
84	120	RC-12	2B3t	62	--	--	--	--	--	--	--	--	--	--
85	120	RC-12	2Cox	+122	--	--	--	--	--	--	--	--	--	--
86	120	RC-32	Ap	21	--	--	--	--	--	--	--	--	--	--
87	120	RC-32	2B2tca	37	58	16.07	5.26	1.91	1.58	0.69	2.31	0.58	0.047	0.035
88	120	RC-32	2B3tca	70	--	--	--	--	--	--	--	--	--	--
89	120	RC-32	3Cca	+80	--	--	--	--	--	--	--	--	--	--
90	120	RC-41	A	8	66	10.70	3.40	0.91	1.09	1.25	2.19	0.55	0.056	0.055
91	120	RC-41	B1t	17	66	12.31	3.91	0.95	0.92	1.15	2.35	0.62	0.049	0.049
92	120	RC-41	B2t	28	58	15.82	5.24	1.31	0.88	0.73	2.33	0.58	0.043	0.041
93	120	RC-41	2B31t	51	51	19.28	6.87	1.86	1.09	0.67	2.46	0.58	0.050	0.031
94	120	RC-41	2B32t	65	56	18.09	6.22	1.94	1.24	0.78	2.24	0.57	0.045	0.039
95	120	RC-41	2Cox	+100	51	19.85	7.01	2.17	1.24	0.66	2.31	0.58	0.052	0.031

Supplementary table 5. Total chemical analysis of fine fraction by induction-coupled plasma spectroscopy--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	Percent of silt-plus-clay fraction									
					SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	ZrO_2
96	415	RC-11	A	9	--	--	--	--	--	--	--	--	--	--
97	415	RC-11	B2t	20	56	16.39	5.94	1.86	1.41	0.98	2.13	0.60	0.111	0.042
98	415	RC-11	B3t	50	--	--	--	--	--	--	--	--	--	--
99	415	RC-11	2C1ca	100	--	--	--	--	--	--	--	--	--	--
100	415	RC-11	2C2ca	+180	--	--	--	--	--	--	--	--	--	--
101	415	RC-37	A	6	--	--	--	--	--	--	--	--	--	--
102	415	RC-37	B1t	18	--	--	--	--	--	--	--	--	--	--
103	415	RC-37	B2tca	45	--	--	--	--	--	--	--	--	--	--
104	415	RC-37	B3tca/K	63	--	--	--	--	--	--	--	--	--	--
105	415	RC-37	2C1ca	109	--	--	--	--	--	--	--	--	--	--
106	415	RC-37	3C2ca	230	--	--	--	--	--	--	--	--	--	--
107	415	RC-37	3C3ca	+240	--	--	--	--	--	--	--	--	--	--
108	600	RC-34	A1	8	--	--	--	--	--	--	--	--	--	--
109	600	RC-34	A3	14	--	--	--	--	--	--	--	--	--	--
110	600	RC-34	B1t	22	--	--	--	--	--	--	--	--	--	--
111	600	RC-34	B2t	37	--	--	--	--	--	--	--	--	--	--
112	600	RC-34	2B3t/ca	54	--	--	--	--	--	--	--	--	--	--
113	600	RC-34	3Cox/ca	89	--	--	--	--	--	--	--	--	--	--
114	600	RC-34	3C1ca	160	--	--	--	--	--	--	--	--	--	--
115	600	RC-34	3C2ca	+210	--	--	--	--	--	--	--	--	--	--
116	600	RC-35	A	5	--	--	--	--	--	--	--	--	--	--
117	600	RC-35	B1t	10	--	--	--	--	--	--	--	--	--	--
118	600	RC-35	B2tca	18	--	--	--	--	--	--	--	--	--	--
119	600	RC-35	B3tca	32	--	--	--	--	--	--	--	--	--	--
120	600	RC-35	2C1ca	54	--	--	--	--	--	--	--	--	--	--
121	600	RC-35	2C2ca	135	--	--	--	--	--	--	--	--	--	--
122	600	RC-35	2C3ca	225	--	--	--	--	--	--	--	--	--	--
123	600	RC-35	2C4ca	+235	--	--	--	--	--	--	--	--	--	--
124	945	RC-6	A	13	--	--	--	--	--	--	--	--	--	--
125	945	RC-6	B1t	30	--	--	--	--	--	--	--	--	--	--
126	945	RC-6	B2t	46	--	--	--	--	--	--	--	--	--	--
127	945	RC-6	2C1ca	96	--	--	--	--	--	--	--	--	--	--
128	945	RC-6	2C2ca	+126	--	--	--	--	--	--	--	--	--	--
129	945	RC-36	A	7	--	--	--	--	--	--	--	--	--	--
130	945	RC-36	B1t	16	--	--	--	--	--	--	--	--	--	--
131	945	RC-36	B2tca	25	--	--	--	--	--	--	--	--	--	--
132	945	RC-36	B3tca	35	--	--	--	--	--	--	--	--	--	--
133	945	RC-36	K	53	--	--	--	--	--	--	--	--	--	--
134	945	RC-36	2C1ca	80	--	--	--	--	--	--	--	--	--	--
135	945	RC-36	3C2ca	103	--	--	--	--	--	--	--	--	--	--
136	945	RC-36	3C3ca	173	--	--	--	--	--	--	--	--	--	--
137	945	RC-36	3C4ca	200	--	--	--	--	--	--	--	--	--	--
138	945	RC-36	4C5ca	227	--	--	--	--	--	--	--	--	--	--
139	945	RC-36	4C6ca	+255	--	--	--	--	--	--	--	--	--	--
140	2,000	RC-33	A1	9	--	--	--	--	--	--	--	--	--	--
141	2,000	RC-33	A3	16	--	--	--	--	--	--	--	--	--	--
142	2,000	RC-33	B1t	24	--	--	--	--	--	--	--	--	--	--
143	2,000	RC-33	B2t	43	--	--	--	--	--	--	--	--	--	--
144	2,000	RC-33	2B3t/ca	58	--	--	--	--	--	--	--	--	--	--
145	2,000	RC-33	2K1	58	--	--	--	--	--	--	--	--	--	--
146	2,000	RC-33	2K2	92	--	--	--	--	--	--	--	--	--	--
147	2,000	RC-33	3C1ca	180	--	--	--	--	--	--	--	--	--	--
148	2,000	RC-33	3C2ca	+220	--	--	--	--	--	--	--	--	--	--
149	2,000	RC-8	A	8	--	--	--	--	--	--	--	--	--	--
150	2,000	RC-8	B2t	22	--	--	--	--	--	--	--	--	--	--
151	2,000	RC-8	2B3tca	72	--	--	--	--	--	--	--	--	--	--
152	2,000	RC-8	2K	112	--	--	--	--	--	--	--	--	--	--
153	2,000	RC-8	2Cca	+162	--	--	--	--	--	--	--	--	--	--

Supplementary table 5. Total chemical analysis of fine fraction by induction-coupled plasma spectroscopy--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	Percent of silt-plus-clay fraction									
					SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	ZrO_2
					Basin chronosequence									
154	7	RC-46A	Ap	20	--	--	--	--	--	--	--	--	--	--
155	7	RC-46A	ACca	40	--	--	--	--	--	--	--	--	--	--
156	7	RC-46A	2Cgca	70	--	--	--	--	--	--	--	--	--	--
157	7	RC-46A	2Cox	98	--	--	--	--	--	--	--	--	--	--
158	7	RC-46A	3Cn	+150	--	--	--	--	--	--	--	--	--	--
159	7	RC-46B	Apca	28	66	12.44	4.21	2.06	3.73	1.28	2.29	0.60	0.059	0.056
160	7	RC-46B	2Cca	60	68	10.57	4.21	2.34	5.55	1.31	2.05	0.72	0.061	0.135
161	7	RC-46B	3Cn*	+150	71	10.72	5.08	2.31	1.95	0.60	2.17	0.95	0.070	0.168
162	20	RC-20	A	9	66	12.72	4.36	1.24	1.36	1.27	2.39	0.57	0.066	0.057
163	20	RC-20	2B1t	15	58	15.12	5.61	1.66	1.48	0.89	2.30	0.58	0.065	0.049
164	20	RC-20	2B2tca	32	50	15.60	5.92	1.94	1.92	0.84	2.14	0.57	0.056	0.054
165	20	RC-20	2B3tca	50	60	14.74	5.22	1.79	1.87	1.02	2.16	0.60	0.047	0.065
166	20	RC-20	3C1ca	130	60	14.03	5.09	1.89	4.39	1.06	2.04	0.62	0.067	0.092
167	20	RC-20	3C2ca	+330	58	14.91	5.54	2.22	5.10	2.26	2.41	0.57	0.067	0.051
168	20	RC-43	A	18	--	--	--	--	--	--	--	--	--	--
169	20	RC-43	B1t	33	--	--	--	--	--	--	--	--	--	--
170	20	RC-43	B2t	44	--	--	--	--	--	--	--	--	--	--
171	20	RC-43	2B3tca	65	--	--	--	--	--	--	--	--	--	--
172	20	RC-43	2C1ca	98	--	--	--	--	--	--	--	--	--	--
173	20	RC-43	3C2ca	+200	--	--	--	--	--	--	--	--	--	--
174	120	RC-27	A	6	56	11.81	4.21	2.17	7.48	1.20	2.53	0.55	0.054	0.052
175	120	RC-27	2B1t	11	65	13.59	4.88	1.91	2.63	1.40	2.77	0.68	0.066	0.070
176	120	RC-27	2B2t	19	59	15.65	5.59	2.09	1.93	1.01	2.65	0.65	0.061	0.051
177	120	RC-27	2B3ca	34	45	10.23	3.33	2.31	17.34	1.12	1.69	0.45	0.035	0.043
178	120	RC-27	3C1ca	74	52	11.15	3.66	2.67	11.83	1.15	1.93	0.52	0.039	0.051
179	120	RC-27	4C2ca	147	56	11.83	4.02	3.88	8.78	1.32	2.17	0.55	0.047	0.052
180	120	RC-27	5C3ca	+225	58	13.02	4.25	3.57	6.46	1.40	2.41	0.58	0.047	0.048
181	415	RC-23	A	3	64	12.12	3.99	1.28	1.80	1.54	2.47	0.60	0.066	0.057
182	415	RC-23	B1tca	7	64	12.10	4.01	1.29	1.83	1.50	2.41	0.62	0.076	0.054
183	415	RC-23	B2tca	14	56	12.04	4.02	1.49	5.16	1.21	2.18	0.57	0.059	0.046
184	415	RC-23	B3tca	29	43	9.02	2.90	1.28	17.3	1.00	1.58	0.42	0.040	0.038
185	415	RC-23	2K	60	26	5.39	1.52	1.71	31.6	0.66	0.83	0.20	0.017	0.019
186	415	RC-23	3C1ca	121	53	10.91	3.81	3.20	7.80	1.15	1.70	0.48	0.217	0.045
187	415	RC-23	3C2ca	170	64	11.46	4.42	4.59	4.39	1.32	1.81	0.52	0.074	0.066
188	415	RC-23	4C3ca	226	55	10.85	3.73	5.16	10.85	1.58	1.81	0.48	0.048	0.046
189	415	RC-23	5C4ca	255	64	11.13	5.16	4.79	4.34	1.40	1.81	0.48	0.045	0.056
190	415	RC-23	5C5ca	310	--	--	--	--	--	--	--	--	--	--
191	415	RC-23	5C6ca	+320	--	--	--	--	--	--	--	--	--	--
192	600	RC-24	A	4	62	13.76	4.82	1.49	1.51	1.37	2.51	0.62	0.071	0.043
193	600	RC-24	B1t	9	60	14.20	5.05	1.59	1.57	1.27	2.47	0.62	0.071	0.042
194	600	RC-24	B2tca	19	60	14.59	5.29	1.86	2.38	1.21	2.34	0.62	0.062	0.039
195	600	RC-24	B3tca	30	45	9.62	3.25	2.21	16.5	1.05	1.60	0.43	0.041	0.030
196	600	RC-24	K	45	24	5.41	1.75	2.67	31.8	0.50	0.80	0.23	0.019	0.016
197	600	RC-24	2C1ca	62	39	10.21	3.48	4.58	15.9	0.78	1.42	0.42	0.032	0.032
198	600	RC-24	2C2ca	87	49	11.32	4.66	6.33	5.55	1.21	1.69	0.62	0.050	0.078
199	600	RC-24	2C3ca	+300	57	11.44	5.19	5.39	8.07	1.83	2.05	0.62	0.059	0.095
200	945	RC-25	Aca	4	--	--	--	--	--	--	--	--	--	--
201	945	RC-25	B1tca	9	--	--	--	--	--	--	--	--	--	--
202	945	RC-25	B2tca	15	45	9.19	3.10	1.82	16.6	1.00	1.65	0.40	0.039	0.036
203	945	RC-25	B3tca	25	--	--	--	--	--	--	--	--	--	--
204	945	RC-25	2K	49	--	--	--	--	--	--	--	--	--	--
205	945	RC-25	2C1ca	65	--	--	--	--	--	--	--	--	--	--
206	945	RC-25	2C2ca	91	--	--	--	--	--	--	--	--	--	--
207	945	RC-25	3C3ca	+130	--	--	--	--	--	--	--	--	--	--
208	945	RC-44	Aca	6	60	12.87	4.28	1.61	3.24	1.28	2.57	0.62	0.063	0.043
209	945	RC-44	B1tca	13	56	13.67	4.61	1.81	4.66	1.05	2.54	0.60	0.052	0.036
210	945	RC-44	B21tca	19	49	11.72	3.98	2.17	9.99	0.95	2.10	0.52	0.037	0.028
211	945	RC-44	B22tca	27	41	9.15	2.98	3.90	15.7	0.89	1.64	0.40	0.037	0.027
212	945	RC-44	B31tca	45	30	7.05	2.25	2.52	25.7	0.75	1.22	0.30	0.028	0.019
213	945	RC-44	2B32tca	86	45	9.34	3.30	6.50	11.3	1.32	1.63	0.43	0.041	0.035
214	945	RC-44	2Cca	+120	56	10.53	3.92	7.23	4.32	1.71	1.95	0.52	0.045	0.042

Supplementary table 5. Total chemical analysis of fine fraction by induction-coupled plasma spectroscopy--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	Percent of silt-plus-clay fraction SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	ZrO_2
215	2,000	RC-26A	A	6	66	11.02	3.32	0.96	1.27	1.58	2.43	0.58	0.071	0.054
216	2,000	RC-26A	B1t	11	62	12.93	4.21	1.44	1.41	1.28	2.47	0.62	0.067	0.042
217	2,000	RC-26A	B21t	20	60	12.99	4.22	1.48	1.37	1.27	2.36	0.60	0.061	0.042
218	2,000	RC-26A	B22tca	29	60	12.76	4.15	1.64	2.13	1.23	2.23	0.60	0.057	0.041
219	2,000	RC-26A	B3tca	40	39	8.32	2.55	2.14	17.9	0.88	1.42	0.38	0.032	0.027
220	2,000	RC-26A	2K	68	15	3.08	0.79	5.56	32.4	0.43	0.46	0.10	0.009	0.009
221	2,000	RC-26A	2C1ca	145	34	6.16	1.59	9.25	16.1	0.78	0.89	0.20	0.014	0.018
222	2,000	RC-26A	2C2ca	247	45	9.70	2.99	7.69	10.1	1.37	1.36	0.32	0.023	0.027
223	2,000	RC-26A	3C3ca	295	--	--	--	--	--	--	--	--	--	--
224	2,000	RC-26B	A	5	--	--	--	--	--	--	--	--	--	--
225	2,000	RC-26B	B1t	10	--	--	--	--	--	--	--	--	--	--
226	2,000	RC-26B	B2tca	16	62	13.40	4.43	2.04	1.80	1.13	2.30	0.58	0.053	0.043
227	2,000	RC-26B	B31tca	25	--	--	--	--	--	--	--	--	--	--
228	2,000	RC-26B	B32tca	36	--	--	--	--	--	--	--	--	--	--
229	2,000	RC-26B	2K	48	--	--	--	--	--	--	--	--	--	--
230	2,000	RC-26B	2C1ca	88	--	--	--	--	--	--	--	--	--	--
231	2,000	RC-26B	2C2ca	+170	--	--	--	--	--	--	--	--	--	--

*Percentages calculated from known percentages of oxides in the sand and the less-than-2mm fractions.

Supplementary table 6. Total chemical analysis of less-than-2-mm fraction by induction-coupled plasma spectroscopy

[Analysts: P. H. Briggs and D. Fey under supervision of L. R. Layman, U. S. Geological Survey. --, not measured]

Methods

Same methods as in supplementary table 5, except that sand fractions were not removed.

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	Percent of less-than-2 mm fraction SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	ZrO_2
1	modern	RC-R	channel gravel		63	12.04	3.36	1.09	2.18	4.65	2.05	0.27	0.039	0.014
2	modern	RC-M	channel gravel		71	13.06	2.12	0.71	2.06	3.61	2.29	0.22	0.032	0.035
			Mountain-front chronosequence											
3	7	RC-38	A1	9	68	11.74	2.05	0.70	1.75	4.76	2.05	0.18	0.031	0.015
4	7	RC-38	2A31	22	73	13.35	2.62	0.90	1.90	4.89	2.53	0.23	0.035	0.020
5	7	RC-38	2A32	33	75	13.04	2.63	0.95	2.01	4.84	2.29	0.25	0.035	0.026
6	7	RC-38	2AC	46	56	9.51	2.35	0.68	1.44	4.11	1.81	0.20	0.023	0.015
7	7	RC-38	3C1ox	85	78	13.52	2.25	0.86	1.87	5.05	2.41	0.22	0.022	0.018
8	7	RC-38	3C2ox	+120	71	13.71	2.30	0.86	1.92	4.25	2.17	0.25	0.021	0.022
9	20	RC-21	A	5	68	12.95	3.38	0.91	1.54	3.41	2.41	0.38	0.059	0.025
10	20	RC-21	B1t	12	70	13.74	3.55	0.98	1.51	3.58	2.53	0.40	0.058	0.028
11	20	RC-21	B2t	25	68	13.99	3.65	1.03	1.38	2.78	2.53	0.43	0.054	0.029
12	20	RC-21	2B3t	38	74	14.33	3.45	1.04	1.62	3.79	2.41	0.33	0.038	0.025
13	20	RC-21	3C1ox	73	76	14.18	2.78	0.88	1.97	5.03	2.41	0.25	0.028	0.015
14	20	RC-21	3C2ox	+110	71	13.93	2.43	0.78	2.08	4.49	2.05	0.22	0.025	0.020
15	20	RC-15	A	8	--	--	--	--	--	--	--	--	--	--
16	20	RC-15	2B2t	23	69	13.69	2.75	1.04	1.96	3.89	2.53	0.30	0.045	0.025
17	20	RC-15	2B3	43	--	--	--	--	--	--	--	--	--	--
18	20	RC-15	2Cox	+68	--	--	--	--	--	--	--	--	--	--

Supplementary table 6. Total chemical analysis of less-than-2-mm fraction by induction-coupled plasma spectroscopy--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	Percent of less-than-2 mm fraction									
					SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	ZrO_2
19	120	RC-31	A1	8	64	13.50	3.45	1.11	1.92	2.87	2.53	0.35	0.065	0.023
20	120	RC-31	A3	19	69	14.01	3.40	1.01	1.66	3.56	2.89	0.33	0.057	0.021
21	120	RC-31	B1t	32	66	13.44	3.95	1.24	1.44	3.19	2.53	0.38	0.067	0.026
22	120	RC-31	B21t	54	70	13.99	3.45	1.11	1.61	3.21	2.65	0.35	0.047	0.023
23	120	RC-31	B22t	81	66	16.34	4.48	1.13	1.97	3.33	2.29	0.40	0.039	0.022
24	120	RC-31	2B31t	123	64	15.58	4.16	1.19	2.57	4.42	1.69	0.35	0.054	0.017
25	120	RC-31	2B32t	145	70	14.84	4.43	1.59	2.59	4.27	1.93	0.35	0.056	0.017
26	120	RC-31	2Cox	+200	67	14.33	3.98	1.48	2.55	4.20	2.17	0.32	0.050	0.016
27	120	RC-17	A	9	--	--	--	--	--	--	--	--	--	--
28	120	RC-17	B1t	20	--	--	--	--	--	--	--	--	--	--
29	120	RC-17	B2t	31	70	13.74	3.49	0.98	1.12	2.79	2.53	0.43	0.043	0.032
30	120	RC-17	B31t	50	--	--	--	--	--	--	--	--	--	--
31	120	RC-17	2B32t	122	--	--	--	--	--	--	--	--	--	--
32	120	RC-17	2Cox	+136	--	--	--	--	--	--	--	--	--	--
33	415	RC-30	A1	9	62	13.25	3.10	1.06	2.20	3.10	2.41	0.30	0.054	0.019
34	415	RC-30	A3	17	69	14.35	3.32	1.13	2.04	3.76	2.65	0.28	0.053	0.015
35	415	RC-30	B1t	29	69	14.63	4.26	1.44	1.99	3.40	2.53	0.38	0.059	0.020
36	415	RC-30	B2t	53	61	14.20	4.01	1.38	1.90	3.33	2.17	0.33	0.038	0.015
37	415	RC-30	2B31t	81	63	15.16	3.43	1.13	2.00	3.58	2.17	0.27	0.040	0.015
38	415	RC-30	2B32t	170	65	14.46	3.86	1.34	2.08	3.60	2.05	0.33	0.067	0.015
39	415	RC-30	2Cox	+250	57	12.85	3.48	1.46	2.06	3.14	2.17	0.28	0.038	0.012
40	600	RC-29	A1	9	64	14.35	4.31	1.56	2.29	3.17	2.41	0.42	0.066	0.026
41	600	RC-29	A3	18	64	14.39	4.11	1.53	2.17	3.44	2.53	0.37	0.066	0.018
42	600	RC-29	B1t	30	62	14.56	4.33	1.56	2.10	3.17	2.29	0.40	0.065	0.018
43	600	RC-29	B2t	50	62	14.29	4.05	1.72	2.13	3.32	2.17	0.37	0.056	0.018
44	600	RC-29	2B31t	79	63	14.74	5.41	1.67	2.43	3.37	2.05	0.48	0.075	0.020
45	600	RC-29	3B32t	167	64	13.89	5.51	2.42	2.76	3.34	2.05	0.47	0.074	0.020
46	600	RC-29	3Cox	+260	66	14.42	4.41	2.12	2.46	3.52	2.17	0.35	0.062	0.013
47	600	RC-16	A	27	--	--	--	--	--	--	--	--	--	--
48	600	RC-16	B1t	47	--	--	--	--	--	--	--	--	--	--
49	600	RC-16	2B2t	72	66	15.61	4.49	1.69	2.38	3.92	2.05	0.38	0.045	0.026
50	600	RC-16	2B3t	127	--	--	--	--	--	--	--	--	--	--
51	600	RC-16	2Cox	+197	--	--	--	--	--	--	--	--	--	--
52	2,000	RC-28	A	7	--	--	--	--	--	--	--	--	--	--
53	2,000	RC-28	B1t	11	--	--	--	--	--	--	--	--	--	--
54	2,000	RC-28	B2t	17	64	15.71	3.72	1.01	1.72	3.61	2.77	0.35	0.043	0.026
55	2,000	RC-28	2B31t	47	--	--	--	--	--	--	--	--	--	--
56	2,000	RC-28	2B32t	141	--	--	--	--	--	--	--	--	--	--
57	2,000	RC-28	2Cox	+270	--	--	--	--	--	--	--	--	--	--
58	2,000	RC-14	A	17	59	12.44	3.13	0.83	1.33	2.43	2.53	0.35	0.062	0.017
59	2,000	RC-14	B1t	32	64	13.12	3.55	1.00	1.37	2.29	2.29	0.38	0.056	0.021
60	2,000	RC-14	B2t	44	61	13.25	3.26	0.96	1.47	2.70	2.05	0.33	0.043	0.016
61	2,000	RC-14	2B31t	84	54	12.48	3.30	1.14	1.73	2.95	1.93	0.28	0.047	0.012
62	2,000	RC-14	3B32t	144	63	13.71	3.36	1.28	2.01	3.49	1.93	0.27	0.049	0.009
63	2,000	RC-14	3Cox	+164	67	14.88	3.05	0.95	2.15	4.08	2.65	0.30	0.036	0.016
					Transition chronosequence									
64	7	RC-40	A	13	--	--	--	--	--	--	--	--	--	--
65	7	RC-40	Bs	46	--	--	--	--	--	--	--	--	--	--
66	7	RC-40	2C1ox	65	--	--	--	--	--	--	--	--	--	--
67	7	RC-40	2C2ox	310	--	--	--	--	--	--	--	--	--	--
68	7	RC-42	A1	6	69	10.87	2.60	0.93	1.61	3.34	2.29	0.32	0.044	0.026
69	7	RC-42	A3	37	73	12.21	2.93	1.04	1.73	3.60	2.41	0.33	0.048	0.025
70	7	RC-42	2Bs	55	75	12.91	3.13	1.11	1.75	3.75	2.41	0.35	0.040	0.025
71	7	RC-42	3Bb	73	73	13.38	3.22	1.13	1.82	3.48	2.41	0.37	0.045	0.027
72	7	RC-42	3Coxb	+200	76	14.22	2.40	0.98	2.27	4.85	2.41	0.22	0.035	0.014

Supplementary table 6. Total chemical analysis of less-than-2-mm fraction by induction-coupled plasma spectroscopy--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	Percent of less-than-2 mm fraction: SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	ZrO_2
73	20	RC-22	A	5	--	--	--	--	--	--	--	--	--	--
74	20	RC-22	B1t	25	--	--	--	--	--	--	--	--	--	--
75	20	RC-22	B2t	43	--	--	--	--	--	--	--	--	--	--
76	20	RC-22	2B3t	57	--	--	--	--	--	--	--	--	--	--
77	20	RC-22	2C1ox	78	--	--	--	--	--	--	--	--	--	--
78	20	RC-22	2C2ox	175	--	--	--	--	--	--	--	--	--	--
79	20	RC-22	3Cca	197	--	--	--	--	--	--	--	--	--	--
80	20	RC-22	3Cn	+240	--	--	--	--	--	--	--	--	--	--
81	120	RC-12	A	9	--	--	--	--	--	--	--	--	--	--
82	120	RC-12	B1t	17	--	--	--	--	--	--	--	--	--	--
83	120	RC-12	B2t	39	--	--	--	--	--	--	--	--	--	--
84	120	RC-12	2B3t	62	--	--	--	--	--	--	--	--	--	--
85	120	RC-12	2Cox	+122	--	--	--	--	--	--	--	--	--	--
86	120	RC-32	Ap	21	--	--	--	--	--	--	--	--	--	--
87	120	RC-32	2B2tca	37	65	14.67	4.55	1.36	1.76	2.52	2.53	0.43	0.056	0.029
88	120	RC-32	2B3tca	70	--	--	--	--	--	--	--	--	--	--
89	120	RC-32	3Cca	+80	--	--	--	--	--	--	--	--	--	--
90	120	RC-41	A	8	70	10.15	2.93	0.75	1.33	2.47	2.17	0.33	0.056	0.029
91	120	RC-41	B1t	17	72	11.85	3.39	0.80	1.16	2.51	2.41	0.43	0.057	0.031
92	120	RC-41	B2t	28	70	14.22	4.45	1.08	1.09	2.06	2.41	0.43	0.045	0.026
93	120	RC-41	2B31t	51	71	14.63	3.42	0.95	1.54	3.33	2.41	0.30	0.034	0.018
94	120	RC-41	2B32t	65	67	14.12	3.38	1.16	1.78	3.54	2.17	0.27	0.041	0.018
95	120	RC-41	2Cox	+100	66	13.27	2.12	0.68	1.75	4.34	2.17	0.15	0.031	0.010
96	415	RC-11	A	9	--	--	--	--	--	--	--	--	--	--
97	415	RC-11	B2t	20	66	15.18	3.93	1.19	1.75	3.22	2.65	0.40	0.101	0.024
98	415	RC-11	B3t	50	--	--	--	--	--	--	--	--	--	--
99	415	RC-11	2C1ca	100	--	--	--	--	--	--	--	--	--	--
100	415	RC-11	2C2ca	+180	--	--	--	--	--	--	--	--	--	--
101	415	RC-37	A	6	--	--	--	--	--	--	--	--	--	--
102	415	RC-37	B1t	18	--	--	--	--	--	--	--	--	--	--
103	415	RC-37	B2tca	45	--	--	--	--	--	--	--	--	--	--
104	415	RC-37	B3tca/K	63	--	--	--	--	--	--	--	--	--	--
105	415	RC-37	2C1ca	109	--	--	--	--	--	--	--	--	--	--
106	415	RC-37	3C2ca	230	--	--	--	--	--	--	--	--	--	--
107	415	RC-37	3C3ca	+240	--	--	--	--	--	--	--	--	--	--
108	600	RC-34	A1	8	--	--	--	--	--	--	--	--	--	--
109	600	RC-34	A3	14	--	--	--	--	--	--	--	--	--	--
110	600	RC-34	B1t	22	--	--	--	--	--	--	--	--	--	--
111	600	RC-34	B2t	37	--	--	--	--	--	--	--	--	--	--
112	600	RC-34	2B3t/ca	54	--	--	--	--	--	--	--	--	--	--
113	600	RC-34	3Cox/ca	89	--	--	--	--	--	--	--	--	--	--
114	600	RC-34	3C1ca	160	--	--	--	--	--	--	--	--	--	--
115	600	RC-34	3C2ca	+210	--	--	--	--	--	--	--	--	--	--
116	600	RC-35	A	5	--	--	--	--	--	--	--	--	--	--
117	600	RC-35	B1t	10	--	--	--	--	--	--	--	--	--	--
118	600	RC-35	B2tca	18	--	--	--	--	--	--	--	--	--	--
119	600	RC-35	B3tca	32	--	--	--	--	--	--	--	--	--	--
120	600	RC-35	2C1ca	54	--	--	--	--	--	--	--	--	--	--
121	600	RC-35	2C2ca	135	--	--	--	--	--	--	--	--	--	--
122	600	RC-35	2C3ca	225	--	--	--	--	--	--	--	--	--	--
123	600	RC-35	2C4ca	+235	--	--	--	--	--	--	--	--	--	--
124	945	RC-6	A	13	--	--	--	--	--	--	--	--	--	--
125	945	RC-6	B1t	30	--	--	--	--	--	--	--	--	--	--
126	945	RC-6	B2t	46	--	--	--	--	--	--	--	--	--	--
127	945	RC-6	2C1ca	96	--	--	--	--	--	--	--	--	--	--
128	945	RC-6	2C2ca	+126	--	--	--	--	--	--	--	--	--	--

Supplementary table 6. Total chemical analysis of less-than-2-mm fraction by induction-coupled plasma spectroscopy--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	Percent of less-than-2 mm fraction									
					SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	ZrO_2
129	945	RC-36	A	7	--	--	--	--	--	--	--	--	--	--
130	945	RC-36	B1t	16	--	--	--	--	--	--	--	--	--	--
131	945	RC-36	B2tca	25	--	--	--	--	--	--	--	--	--	--
132	945	RC-36	B3tca	35	--	--	--	--	--	--	--	--	--	--
133	945	RC-36	K	53	--	--	--	--	--	--	--	--	--	--
134	945	RC-36	2C1ca	80	--	--	--	--	--	--	--	--	--	--
135	945	RC-36	3C2ca	103	--	--	--	--	--	--	--	--	--	--
136	945	RC-36	3C3ca	173	--	--	--	--	--	--	--	--	--	--
137	945	RC-36	3C4ca	200	--	--	--	--	--	--	--	--	--	--
138	945	RC-36	4C5ca	227	--	--	--	--	--	--	--	--	--	--
139	945	RC-36	4C6ca	+255	--	--	--	--	--	--	--	--	--	--
140	2,000	RC-33	A1	9	--	--	--	--	--	--	--	--	--	--
141	2,000	RC-33	A3	16	--	--	--	--	--	--	--	--	--	--
142	2,000	RC-33	B1t	24	--	--	--	--	--	--	--	--	--	--
143	2,000	RC-33	B2t	43	--	--	--	--	--	--	--	--	--	--
144	2,000	RC-33	2B3t/ca	58	--	--	--	--	--	--	--	--	--	--
145	2,000	RC-33	2K1	58	--	--	--	--	--	--	--	--	--	--
146	2,000	RC-33	2K2	92	--	--	--	--	--	--	--	--	--	--
147	2,000	RC-33	3C1ca	180	--	--	--	--	--	--	--	--	--	--
148	2,000	RC-33	3C2ca	+220	--	--	--	--	--	--	--	--	--	--
149	2,000	RC-8	A	8	--	--	--	--	--	--	--	--	--	--
150	2,000	RC-8	B2t	22	--	--	--	--	--	--	--	--	--	--
151	2,000	RC-8	2B3tca	72	--	--	--	--	--	--	--	--	--	--
152	2,000	RC-8	2K	112	--	--	--	--	--	--	--	--	--	--
153	2,000	RC-8	2Cca	+162	--	--	--	--	--	--	--	--	--	--
					Basin chronosequence									
154	7	RC-46A	Ap	20	--	--	--	--	--	--	--	--	--	--
155	7	RC-46A	ACca	40	--	--	--	--	--	--	--	--	--	--
156	7	RC-46A	2Cgca	70	--	--	--	--	--	--	--	--	--	--
157	7	RC-46A	2Cox	98	--	--	--	--	--	--	--	--	--	--
158	7	RC-46A	3Cn	+150	--	--	--	--	--	--	--	--	--	--
159	7	RC-46B	Apca	28	66	11.66	3.66	1.82	3.38	1.33	2.17	0.52	0.056	0.047
160	7	RC-46B	2Cca	60	71	9.60	3.42	1.84	4.35	1.55	1.93	0.53	0.053	0.093
161	7	RC-46B	3Cn	+150	71	12.23	3.23	1.36	2.85	2.79	2.17	0.38	0.048	0.042
162	20	RC-20	A	9	75	11.08	3.36	0.91	1.37	2.44	2.29	0.38	0.057	0.033
163	20	RC-20	2B1t	15	73	12.67	4.39	1.23	1.45	2.28	2.29	0.40	0.063	0.032
164	20	RC-20	2B2tca	32	72	13.42	4.42	1.19	1.73	2.80	2.29	0.35	0.061	0.024
165	20	RC-20	2B3tca	50	77	11.93	3.65	0.91	1.80	3.17	2.17	0.30	0.061	0.027
166	20	RC-20	3C1ca	130	73	9.45	3.10	0.71	1.89	2.65	1.81	0.23	0.058	0.020
167	20	RC-20	3C2ca	+330	71	13.95	2.70	1.01	2.28	3.98	2.41	0.20	0.040	0.013
168	20	RC-43	A	18	--	--	--	--	--	--	--	--	--	--
169	20	RC-43	B1t	33	--	--	--	--	--	--	--	--	--	--
170	20	RC-43	B2t	44	--	--	--	--	--	--	--	--	--	--
171	20	RC-43	2B3tca	65	--	--	--	--	--	--	--	--	--	--
172	20	RC-43	2C1ca	98	--	--	--	--	--	--	--	--	--	--
173	20	RC-43	3C2ca	+200	--	--	--	--	--	--	--	--	--	--
174	120	RC-27	A	6	62	10.93	3.66	1.82	5.94	1.44	2.29	0.45	0.048	0.038
175	120	RC-27	2B1t	11	66	11.64	4.11	1.44	2.38	1.62	2.29	0.48	0.053	0.045
176	120	RC-27	2B2t	19	61	14.18	5.41	1.74	2.06	1.48	2.53	0.53	0.062	0.036
177	120	RC-27	2B3ca	34	55	9.57	3.29	1.97	13.4	1.29	1.69	0.38	0.040	0.032
178	120	RC-27	3C1ca	74	61	10.08	3.22	2.16	8.91	1.37	1.81	0.42	0.039	0.040
179	120	RC-27	4C2ca	147	62	10.98	3.38	3.13	7.16	1.71	2.05	0.42	0.044	0.036
180	120	RC-27	5C3ca	+225	66	10.23	3.68	1.86	6.42	1.94	1.93	0.33	0.057	0.020

Supplementary table 6. Total chemical analysis of less-than-2-mm fraction by induction-coupled plasma spectroscopy--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	Percent of less-than-2 mm fraction									
					SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	ZrO_2
181	415	RC-23	A	3	64	11.04	3.25	1.13	1.87	1.86	2.41	0.42	0.059	0.033
182	415	RC-23	B1tca	7	66	11.27	3.20	1.13	2.08	2.09	2.41	0.43	0.057	0.036
183	415	RC-23	B2tca	14	60	11.08	3.16	1.28	6.21	1.91	2.17	0.40	0.047	0.029
184	415	RC-23	B3tca	29	46	9.15	2.07	1.06	17.8	2.05	1.45	0.25	0.027	0.017
185	415	RC-23	2K	60	46	8.75	1.33	1.21	19.7	2.35	1.81	0.15	0.017	0.011
186	415	RC-23	3C1ca	121	63	12.12	3.25	2.29	4.90	2.52	2.05	0.32	0.308	0.022
187	415	RC-23	3C2ca	170	69	12.40	2.85	2.22	3.08	2.74	2.05	0.28	0.080	0.030
188	415	RC-23	4C3ca	226	66	12.08	2.30	2.37	5.79	2.98	2.05	0.27	0.036	0.021
189	415	RC-23	5C4ca	255	70	13.02	2.56	1.59	2.80	3.42	2.29	0.22	0.030	0.028
190	415	RC-23	5C5ca	310	--	--	--	--	--	--	--	--	--	--
191	415	RC-23	5C6ca	+320	--	--	--	--	--	--	--	--	--	--
192	600	RC-24	A	4	60	11.80	4.05	1.36	1.43	1.48	2.41	0.48	0.058	0.029
193	600	RC-24	B1t	9	63	12.72	4.45	1.51	1.54	1.50	2.41	0.50	0.059	0.030
194	600	RC-24	B2tca	19	60	12.95	4.59	1.77	2.29	1.40	2.29	0.50	0.054	0.029
195	600	RC-24	B3tca	30	47	9.17	3.06	2.16	14.7	1.21	1.69	0.37	0.038	0.022
196	600	RC-24	K	45	29	5.67	1.75	2.55	28.1	0.88	0.96	0.22	0.018	0.015
197	600	RC-24	2C1ca	62	55	10.96	2.78	2.80	9.82	2.41	1.81	0.32	0.028	0.025
198	600	RC-24	2C2ca	87	64	11.81	5.11	2.34	2.87	3.13	2.05	0.65	0.057	0.034
199	600	RC-24	2C3ca	+300	71	12.27	2.83	1.08	2.06	3.58	2.41	0.33	0.035	0.031
200	945	RC-25	Aca	4	--	--	--	--	--	--	--	--	--	--
201	945	RC-25	B1tca	9	--	--	--	--	--	--	--	--	--	--
202	945	RC-25	B2tca	15	46	9.00	3.03	1.87	16.9	1.83	1.69	0.37	0.039	0.023
203	945	RC-25	B3tca	25	--	--	--	--	--	--	--	--	--	--
204	945	RC-25	2K	49	--	--	--	--	--	--	--	--	--	--
205	945	RC-25	2C1ca	65	--	--	--	--	--	--	--	--	--	--
206	945	RC-25	2C2ca	91	--	--	--	--	--	--	--	--	--	--
207	945	RC-25	3C3ca	+130	--	--	--	--	--	--	--	--	--	--
208	945	RC-44	Aca	6	64	11.19	3.69	1.48	3.17	1.51	2.29	0.45	0.050	0.026
209	945	RC-44	B1tca	13	58	11.68	3.95	1.66	4.35	1.24	2.29	0.45	0.040	0.025
210	945	RC-44	B21tca	19	54	10.66	3.53	2.02	9.27	1.17	2.05	0.42	0.036	0.023
211	945	RC-44	B22tca	27	46	8.47	2.70	3.67	13.9	1.19	1.57	0.33	0.032	0.017
212	945	RC-44	B31tca	45	36	7.16	2.32	2.60	22.4	1.15	1.33	0.28	0.028	0.013
213	945	RC-44	2B32tca	86	59	10.42	3.30	4.36	6.67	2.21	1.93	0.35	0.043	0.018
214	945	RC-44	2Cca	+120	66	10.23	3.16	3.98	2.80	2.30	1.93	0.32	0.038	0.018
215	2,000	RC-26A	A	6	70	11.00	2.53	0.78	1.31	2.33	2.29	0.38	0.058	0.032
216	2,000	RC-26A	B1t	11	65	11.98	3.12	1.08	1.31	2.06	2.41	0.40	0.052	0.029
217	2,000	RC-26A	B21t	20	66	12.31	3.35	1.23	1.33	1.94	2.53	0.42	0.054	0.027
218	2,000	RC-26A	B22tca	29	65	11.89	3.06	1.26	1.86	2.14	2.17	0.40	0.045	0.024
219	2,000	RC-26A	B3tca	40	46	8.58	2.09	2.07	16.6	1.55	1.57	0.27	0.028	0.018
220	2,000	RC-26A	2K	68	33	5.90	1.10	4.81	23.9	1.55	1.20	0.13	0.017	0.007
221	2,000	RC-26A	2C1ca	145	56	9.77	1.42	4.41	7.54	2.82	1.93	0.18	0.021	0.011
222	2,000	RC-26A	2C2ca	247	66	11.42	1.39	1.54	2.41	3.57	2.17	0.12	0.017	0.008
223	2,000	RC-26A	3C3ca	295	--	--	--	--	--	--	--	--	--	--
224	2,000	RC-26B	A	5	--	--	--	--	--	--	--	--	--	--
225	2,000	RC-26B	B1t	10	--	--	--	--	--	--	--	--	--	--
226	2,000	RC-26B	B2tca	16	67	12.57	3.65	1.56	1.72	1.90	2.53	0.48	0.043	0.033
227	2,000	RC-26B	B31tca	25	--	--	--	--	--	--	--	--	--	--
228	2,000	RC-26B	B32tca	36	--	--	--	--	--	--	--	--	--	--
229	2,000	RC-26B	2K	48	--	--	--	--	--	--	--	--	--	--
230	2,000	RC-26B	2C1ca	88	--	--	--	--	--	--	--	--	--	--
231	2,000	RC-26B	2C2ca	+170	--	--	--	--	--	--	--	--	--	--

Supplementary table 7, part 1. Horizon weights of sand, silt, clay, carbon, organic phosphorus, $CaCO_3$, and clay minerals

[Analyst: Marith C. Reheis, U.S. Geological Survey. --, not measured]

Methods

Profile weights of soil properties (g/cm^2/column of soil) are calculated from the property percentage, bulk density, and texture of each horizon. The pedogenic increase from the amount of the property in the parent material is calculated by estimating the property percentage, bulk density, and texture in the original deposit (method modified from Machette, 1978 and 1985). Weights are calculated for each horizon, summed to give the total profile weight in a soil, and standardized to 250 cm depth (in the regression equations in the text) to eliminate bias caused by different depths of sampling (backhoe pits versus hand-dug holes).

Two basic equations are used to calculate pedogenic increase for clay, silt, organic phosphorus, and $CaCO_3$. Equation 1 is used to calculate pedogenic increase in horizon weight of clay and silt (substitute appropriate silt percentages when calculating silt weights):

$$1.\quad \text{g clay} = \left(\left(\frac{\text{clay\%}}{100}\right)(\text{BDf})\left(\frac{100 - \text{salts\%}}{100}\right)(\text{H})\right) - \left(\left(\frac{\text{i clay\%}}{100}\right)(\text{i BDf})\left(\frac{100 - \text{i salts\%}}{100}\right)(\text{H})\right)$$

where BDf is the bulk density of the <2-mm fraction, H is the horizon thickness, salts include organic matter, $CaCO_3$, and gypsum (if present), and the letter "i" designates an estimate of the parent-material state. The parent-material $CaCO_3$ content of all Rock Creek soils except soils RC-27, RC-36, and RC-25 is assumed to be zero. This equation includes a factor to account for salts and organic matter because particle size is measured on an organic-free and salt-free basia. Equation 2 is used to calculate pedogenic weights of organic phosphorus (phos) and $CaCO_3$ (again, substitute $CaCO_3$ percentages in place of organic phosphorus percentages when calculating $CaCO_3$ weights):

$$2.\quad \text{g phos} = \left(\left(\frac{\text{phos\%}}{100}\right)(\text{BDf})(\text{H})\right) - \left(\left(\frac{\text{i phos\%}}{100}\right)(\text{i BDf})(\text{H})\right)$$

Profile weights for sand, carbon, clay minerals, and major oxides are not corrected for the estimated parent material contents. Values for sand are calculated using the first term of equation 1 above, substituting the appropriate sand percentages for clay percentages. Values for carbon and major oxides of the less-than-2 mm fraction (supplementary table 7, part 2) are calculated using the first term of equation 2 above, substituting the appropriate property percentages for the percentage of organic phosphorus. Horizon weights for clay minerals are calculated by equation 3:

$$3.\quad \text{g clay mineral} = \left(\frac{\text{clay mineral\%}}{100}\right)\left(\frac{\text{clay\%}}{100}\right)(\text{H})(\text{BDf})\left(\frac{100 - \text{salts\%}}{100}\right)$$

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	horizon weight (g/cm^2/horizon column) Sand	Silt	Clay	Carbon	Organic phosphorus	$CaCO_3$	Kaolinite	Chlorite	Mica	Mixed-layer smectite-illite	Smectite
1	modern	RC-R	channel gravel		--	--	--	--	--	--	--	--	--	--	--
2	modern	RC-M	channel gravel		--	--	--	--	--	--	--	--	--	--	--
								Mountain-front chronosequence							
3	7	RC-38	A1	9	5.8	-0.05	-0.10	0.21	0.0014	0	0.064	0.026	0.10	0.029	0.017
4	7	RC-38	2A31	22	7.9	.32	.15	.13	.0024	0	.072	.036	.15	.069	.032
5	7	RC-38	2A32	33	6.9	.69	.11	.032	.0015	0	.046	.005	.043	.12	.022
6	7	RC-38	2AC	46	10.	.85	.05	.029	.0019	0	.025	.008	.046	.16	.023
7	7	RC-38	3C1ox	85	8.9	0	0	.016	.0004	0	.011	.004	.038	.12	.009
8	7	RC-38	3C2ox	+120	10.	0	0	.033	0	0	--	--	--	--	--
9	20	RC-21	A	5	3.6	.42	.12	.17	.0024	0	.11	.025	.14	.50	.049
10	20	RC-21	B1t	12	5.7	.81	.46	.26	.0026	0	.39	.058	.45	.38	.17
11	20	RC-21	B2t	25	8.1	.80	1.1	.33	.0027	0	.68	.054	.68	.89	.41
12	20	RC-21	2B3t	38	9.5	1.6	1.2	.083	.0009	0	.46	.040	.24	.40	.56
13	20	RC-21	3C1ox	73	8.9	0	0	.016	.0006	0	.006	.001	.010	.054	.003
14	20	RC-21	3C2ox	+110	9.7	0	0	.015	.0001	0	--	--	--	--	--
15	20	RC-15	A	8	--	--	--	--	--	--	--	--	--	--	--
16	20	RC-15	2B2t	23	--	--	--	--	--	--	--	--	--	--	--
17	20	RC-15	2B3	43	--	--	--	--	--	--	--	--	--	--	--
18	20	RC-15	2Cox	+68	--	--	--	--	--	--	--	--	--	--	--
19	120	RC-31	A1	8	4.2	.42	.12	.26	0.0020	0	.18	.041	.26	.17	.027
20	120	RC-31	A3	19	6.4	.97	.40	.25	0.0036	0	.25	.045	.50	.26	.090
21	120	RC-31	B1t	32	5.9	1.8	1.0	.21	0.0018	0	.46	.051	.32	.59	.25
22	120	RC-31	B21t	54	16.	3.9	2.4	.48	0.0031	0	.84	.34	.80	.61	.99
23	120	RC-31	B22t	81	18.	1.9	3.5	.35	0.0039	0	.56	.20	1.1	2.3	.46
24	120	RC-31	2B31t	123	37.	2.1	1.0	.069	0.0018	0	.25	.19	.54	1.6	.22
25	120	RC-31	2B32t	145	8.3	.49	0.15	.005	0.0017	0	.013	.008	.042	.25	.046
26	120	RC-31	2Cox	+200	29.	0	0	.006	0	0	.007	.035	.17	.26	.071

Supplementary table 7, part 1. Horizon weights of sand, silt, clay, carbon, organic phosphorus, $CaCO_3$, and clay minerals--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	horizon weight (g/cm^2/horizon column) Sand	Silt	Clay	Carbon	Organic phosphorus	$CaCO_3$	Kaolinite	Chlorite	Mica	Mixed-layer smectite-illite	Smectite
27	120	RC-17	A	9	--	--	--	--	--	--	--	--	--	--	--
28	120	RC-17	B1t	20	--	--	--	--	--	--	--	--	--	--	--
29	120	RC-17	B2t	31	--	--	--	--	--	--	--	--	--	--	--
30	120	RC-17	B31t	50	--	--	--	--	--	--	--	--	--	--	--
31	120	RC-17	2B32t	122	--	--	--	--	--	--	--	--	--	--	--
32	120	RC-17	2Cox	+136	--	--	--	--	--	--	--	--	--	--	--
33	415	RC-30	A1	9	6.0	-.14	-.37	.45	.0028	0	.071	.088	.64	.018	.071
34	415	RC-30	A3	17	6.4	.04	-.13	.24	.0025	0	.13	.070	.58	.00	.039
35	415	RC-30	B1t	29	8.5	1.4	.71	.25	.0025	0	.23	.031	.79	.32	.11
36	415	RC-30	B2t	53	16.	.92	2.4	.32	.0035	0	.073	.073	.55	2.4	.44
37	415	RC-30	2B31t	81	20.	.69	2.7	.21	.0027	0	.17	.083	.42	2.7	.46
38	415	RC-30	2B32t	170	69.	1.7	4.5	.083	0	0	.35	.18	2.0	4.9	.88
39	415	RC-30	2Cox	+250	24.	0	.57	.011	.0010	0	.022	.044	.24	1.6	.22
40	600	RC-29	A1	9	2.2	.01	0	.10	.0010	0	.084	.012	.15	.088	.046
41	600	RC-29	A3	18	4.0	.33	.16	.11	.0013	0	.092	.018	.33	.11	.062
42	600	RC-29	B1t	30	8.2	1.5	1.1	.24	.0035	0	.49	.038	.75	.30	.21
43	600	RC-29	B2t	50	9.6	1.4	1.1	.25	.0018	0	.48	.13	.80	.13	.36
44	600	RC-29	2B31t	79	15.	1.2	.84	.33	.0026	0	.30	.068	1.1	.36	.27
45	600	RC-29	3B32t	167	76.	3.4	2.6	0	.0080	0	.20	.14	1.3	3.4	1.1
46	600	RC-29	3Cox	+260	52.	0	4.3	0	0	0	.19	.062	1.2	3.1	1.1
47	600	RC-16	A	27	--	--	--	--	--	--	--	--	--	--	--
48	600	RC-16	B1t	47	--	--	--	--	--	--	--	--	--	--	--
49	600	RC-16	2B2t	72	--	--	--	--	--	--	--	--	--	--	--
50	600	RC-16	2B3t	127	--	--	--	--	--	--	--	--	--	--	--
51	600	RC-16	2Cox	+197	--	--	--	--	--	--	--	--	--	--	--
52	2,000	RC-28	A	7	2.5	-.07	.0	.11	--	0	--	--	--	--	--
53	2,000	RC-28	B1t	11	3.1	.07	.07	.075	--	0	--	--	--	--	--
54	2,000	RC-28	B2t	17	4.4	.19	.29	.13	--	0	--	--	--	--	--
55	2,000	RC-28	2B31t	47	8.7	.77	.92	.064	--	0	--	--	--	--	--
56	2,000	RC-28	2B32t	141	37.	1.5	2.8	.086	--	0	--	--	--	--	--
57	2,000	RC-28	2Cox	+270	67.	0	2.9	.060	--	0	--	--	--	--	--
58	2,000	RC-14	A	17	12.	-1.1	1.2	--	.0074	0	.49	0	1.8	1.6	0
59	2,000	RC-14	B1t	32	12.	-.51	2.2	--	.0056	0	.67	0	1.2	2.4	.22
60	2,000	RC-14	B2t	44	11.	-.52	2.0	--	.0209	0	.90	0	.56	2.0	.30
61	2,000	RC-14	2B31t	84	26.	1.2	3.0	--	.0047	0	.50	0	2.2	1.3	.60
62	2,000	RC-14	3B32t	144	36.	0	2.9	--	.0064	0	.049	0	.25	2.6	.99
63	2,000	RC-14	3Cox	+164	10.	0	.19	--	0	0	.021	0	.08	.28	.06
							Transition chronosequence								
64	7	RC-40	A	13	10.	-.31	.55	--	--	0	--	--	--	--	--
65	7	RC-40	Bs	46	19.	3.7	1.2	--	--	0	--	--	--	--	--
66	7	RC-40	2C1ox	75	9.4	0	0	--	--	0	--	--	--	--	--
67	7	RC-40	2C2ox	310	103	0	0	--	--	0	--	--	--	--	--
68	7	RC-42	A1	6	2.3	-.15	-.23	.16	--	0	.11	.025	.11	.071	.039
69	7	RC-42	A3	37	8.4	-1.5	-.96	.33	--	0	.34	.074	.44	.23	.14
70	7	RC-42	2Bs	55	14.	-0.22	.79	.26	--	0	.82	.11	.93	0	.38
71	7	RC-42	3Bb	73	8.8	2.2	.73	.042	--	0	.52	.066	.50	0	.24
72	7	RC-42	3Coxb	+200	56.	0	0	.13	--	0	.52	0	.36	.037	.32
73	20	RC-22	A	5	3.0	.38	.05	.22	--	0	.21	0.038	.34	.11	.053
74	20	RC-22	B1t	25	11.	.83	.39	.38	--	0	.52	0.16	.97	.81	.16
75	20	RC-22	B2t	43	8.6	2.9	1.6	.22	--	0	.46	0	.64	1.3	.15
76	20	RC-22	2B3t	57	18.	2.2	1.4	.43	--	0	.29	0.13	1.0	.33	.42
77	20	RC-22	2C1ox	78	32.	1.3	1.4	.029	--	0	.38	0.18	.79	.68	.51
78	20	RC-22	2C2ox	175	31.	0	0	.052	--	0	.42	0	.51	.78	.40
79	20	RC-22	3Cca	197	7.9	0	0	.050	--	.28	--	--	--	--	--
80	20	RC-22	3Cn	+240	14.	0	0	.006	--	0	--	--	--	--	--
81	120	RC-12	A	9	--	--	--	--	--	--	--	--	--	--	--
82	120	RC-12	B1t	17	--	--	--	--	--	--	--	--	--	--	--
83	120	RC-12	B2t	39	--	--	--	--	--	--	--	--	--	--	--
84	120	RC-12	2B3t	62	--	--	--	--	--	--	--	--	--	--	--
85	120	RC-12	2Cox	+122	--	--	--	--	--	--	--	--	--	--	--

Supplementary table 7, part 1. Horizon weights of sand, silt, clay, carbon, organic phosphorus, $CaCO_3$, and clay minerals--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	horizon weight (g/cm^2/horizon column) Sand	Silt	Clay	Carbon	Organic phosphorus	$CaCO_3$	Kaolinite	Chlorite	Mica	Mixed-layer smectite-illite	Smectite
86	120	RC-32	Ap	21	7.2	2.7	12.	.77	--	0	2.1	.60	1.8	7.6	3.0
87	120	RC-32	2B2tca	37	5.7	.67	2.0	.16	--	.06	.65	.084	.56	1.0	.45
88	120	RC-32	2B3tca	70	23.	4.3	5.4	.77	--	1.6	2.5	.38	1.7	1.4	1.7
89	120	RC-32	3Cca	+80	3.2	.08	.09	.003	--	.01	.064	.008	.036	.060	.02
90	120	RC-41	A	8	3.4	-.11	-.24	0.4	.0035	0	.37	0	.22	.020	.053
91	120	RC-41	B1t	17	4.0	2.0	1.2	.19	.0023	0	.85	.034	.33	.36	.16
92	120	RC-41	B2t	28	4.3	1.0	2.5	.20	.0025	0	1.3	.032	.35	1.2	.29
93	120	RC-41	2B31t	51	10.	0	2.1	.27	.0019	0	1.2	.062	.25	1.3	.31
94	120	RC-41	2B32t	65	7.1	0	1.3	.011	.0002	0	.59	.064	.21	.55	.21
95	120	RC-41	2Cox	+100	12.	0	.44	.008	.0006	0	.20	.017	.074	.46	.074
96	415	RC-11	A	9	--	--	--	--	--	--	--	--	--	--	--
97	415	RC-11	B2t	20	--	--	--	--	--	--	--	--	--	--	--
98	415	RC-11	B3t	50	--	--	--	--	--	--	--	--	--	--	--
99	415	RC-11	2C1ca	100	--	--	--	--	--	--	--	--	--	--	--
100	415	RC-11	2C2ca	+180	--	--	--	--	--	--	--	--	--	--	--
101	415	RC-37	A	6	4.0	-.01	.16	.22	--	0	.21	.040	.38	.33	.050
102	415	RC-37	B1t	18	6.6	.73	1.3	.25	--	0	.60	.078	.42	1.2	.29
103	415	RC-37	B2tca	45	21.	0	4.1	.69	--	.07	2.0	.22	1.2	1.9	1.7
104	415	RC-37	B3tca/K	63	5.3	.99	1.9	.25	--	8.7	.76	.096	.41	.83	.99
105	415	RC-37	2C1ca	109	7.1	.67	1.2	.14	--	6.9	.45	.14	.39	.62	.71
106	415	RC-37	3C2ca	230	61.	.79	1.5	.007	--	11.	1.0	.18	.84	.40	1.2
107	415	RC-37	3C3ca	+240	--	--	--	--	--	--	--	--	--	--	--
108	600	RC-34	A1	8	5.6	.67	.51	.22	--	0	.34	0	.48	.65	.13
109	600	RC-34	A3	14	4.3	.45	.31	.20	--	0	.30	.068	.37	.27	.14
110	600	RC-34	B1t	22	5.7	.77	.57	.20	--	0	.25	.12	.52	.67	.12
111	600	RC-34	B2t	37	8.7	.90	1.8	.27	--	0	.49	.070	1.62	.67	.49
112	600	RC-34	2B3t/ca	54	7.3	.49	.39	.10	--	0.02	.11	.050	.23	.39	.22
113	600	RC-34	3Cox/ca	89	6.5	3.0	.30	.023	--	3.5	.065	.020	.075	.065	.065
114	600	RC-34	3C1ca	160	24.	0	0	.020	--	4.3	.17	.040	.10	.097	.17
115	600	RC-34	3C2ca	+210	18.	0	0	.002	--	1.3	--	--	--	--	--
116	600	RC-35	A	5	4.0	-.22	-.07	--	--	0	--	--	--	--	--
117	600	RC-35	B1t	10	3.7	-.36	.70	--	--	0	--	--	--	--	--
118	600	RC-35	B2tca	18	4.7	.29	1.4	--	--	.28	--	--	--	--	--
119	600	RC-35	B3tca	32	8.7	.19	.53	--	--	7.8	--	--	--	--	--
120	600	RC-35	2C1ca	54	6.2	.00	.17	--	--	3.8	--	--	--	--	--
121	600	RC-35	2C2ca	135	23.	1.4	.81	--	--	9.3	--	--	--	--	--
122	600	RC-35	2C3ca	225	28.	0	0	--	--	4.2	--	--	--	--	--
123	600	RC-35	2C4ca	+235	3.2	0	0	--	--	.17	--	--	--	--	--
124	945	RC-6	A	13	--	--	--	--	--	--	--	--	--	--	--
125	945	RC-6	B1t	30	--	--	--	--	--	--	--	--	--	--	--
126	945	RC-6	B2t	46	--	--	--	--	--	--	--	--	--	--	--
127	945	RC-6	2C1ca	96	--	--	--	--	--	--	--	--	--	--	--
128	945	RC-6	2C2ca	+126	--	--	--	--	--	--	--	--	--	--	--
129	945	RC-36	A	7	1.9	.67	.28	.009	--	0	.29	.031	.21	.013	.094
130	945	RC-36	B1t	16	3.6	.33	1.7	.19	--	0	.60	.023	.60	.90	.21
131	945	RC-36	B2tca	25	3.3	.46	1.2	.12	--	.03	.33	.12	.30	.28	.50
132	945	RC-36	B3tca	35	4.4	1.9	1.8	.12	--	5.0	.83	.13	.45	.22	.31
133	945	RC-36	K	53	3.6	3.0	2.6	.13	--	13.	1.1	.19	.47	.063	.75
134	945	RC-36	2C1ca	80	10.	4.8	3.3	.045	--	6.3	2.0	.023	1.2	.87	1.3
135	945	RC-36	3C2ca	103	4.8	0	0	.32	--	.05	2.2	.36	1.4	0	2.7
136	945	RC-36	3C3ca	173	7.1	0	0	1.8	--	.22	--	--	--	--	--
137	945	RC-36	3C4ca	200	16.	0	0	.46	--	1.0	2.7	.48	1.60	0	3.20
138	945	RC-36	4C5ca	227	9.7	0	0	.010	--	.36	--	--	--	--	--
139	945	RC-36	4C6ca	+255	6.4	0	0	.008	--	1.8	.16	.015	.12	0	.21
140	2,000	RC-33	A1	9	1.2	.20	.25	.050	--	0	.17	.051	.15	.20	.051
141	2,000	RC-33	A3	16	2.1	.79	1.4	.12	--	0	.50	.089	.55	.32	.32
142	2,000	RC-33	B1t	24	2.9	.11	2.4	.20	--	0	.44	.067	.50	2.0	.34
143	2,000	RC-33	B2t	43	9.8	-.27	8.3	.49	--	0	2.8	.22	2.4	3.7	2.1
144	2,000	RC-33	2B3t/ca	58	2.9	.06	0.52	.10	--	0.86	.13	0	.13	.65	.11
145	2,000	RC-33	2K1	58	2.9	.06	0.52	.066	--	0.86	.13	0	.13	.65	.11
146	2,000	RC-33	2K2	92	12.	.13	1.3	.25	--	3.9	.24	0	.26	1.0	.86
147	2,000	RC-33	3C1ca	180	37.	0	4.3	.15	--	2.0	.51	0	.29	4.7	1.7
148	2,000	RC-33	3C2ca	+220	11.	0	0	.006	--	.37	.14	0	.16	1.5	.47
149	2,000	RC-8	A	8	--	--	--	--	--	--	--	--	--	--	--
150	2,000	RC-8	B2t	22	--	--	--	--	--	--	--	--	--	--	--
151	2,000	RC-8	2B3tca	72	--	--	--	--	--	--	--	--	--	--	--
152	2,000	RC-8	2K	112	--	--	--	--	--	--	--	--	--	--	--
153	2,000	RC-8	2Cca	+162	--	--	--	--	--	--	--	--	--	--	--

Supplementary table 7, part 1. Horizon weights of sand, silt, clay, carbon, organic phosphorus, $CaCO_3$, and clay minerals--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	horizon weight (g/cm^2/horizon column) Sand	Silt	Clay	Carbon	Organic phosphorus	$CaCO_3$	Kaolinite	Chlorite	Mica	Mixed-layer smectite-illite	Smectite
								Basin chronosequence							
154	7	RC-46A	Ap	20	6.7	--	-.37	.53	--	.43	--	--	--	--	--
155	7	RC-46A	ACca	40	17.	--	.76	.12	--	1.7	--	--	--	--	--
156	7	RC-46A	2Cgca	70	13.	--	0	.54	--	1.5	--	--	--	--	--
157	7	RC-46A	2Cox	98	20.	--	0	.090	--	.18	--	--	--	--	--
158	7	RC-46A	3Cn	+150	12.	--	0	.017	--	.01	--	--	--	--	--
159	7	RC-46B	Apca	28	9.6	--	.63	.71	--	1.1	--	--	--	--	--
160	7	RC-46B	2Cca	60	15.	--	-.28	.11	--	.71	--	--	--	--	--
161	7	RC-46B	3Cn	+150	21.	--	0	.029	--	.01	--	--	--	--	--
162	20	RC-20	A	9	6.5	1.1	.89	.25	0	0	.71	0	.67	.50	.28
163	20	RC-20	2B1t	15	4.3	.13	1.6	.12	.0023	0	.53	0	.33	1.3	.35
164	20	RC-20	2B2tca	32	9.6	.65	2.2	.11	.0043	.35	1.0	0	.50	.71	.87
165	20	RC-20	2B3tca	50	11.	0	.10	.065	.0017	.13	.35	.010	.19	.15	.29
166	20	RC-20	3C1ca	130	33.	0	0	.026	.0009	4.9	.60	0	.34	.23	.71
167	20	RC-20	3C2ca	+330	51.	0	0	.011	.0004	.16	--	--	--	--	--
168	20	RC-43	A	18	7.6	-.05	2.7	.65	--	0	--	--	--	--	--
169	20	RC-43	B1t	33	9.1	-.55	.02	.43	--	0	--	--	--	--	--
170	20	RC-43	B2t	44	6.1	.42	2.2	.35	--	0	--	--	--	--	--
171	20	RC-43	2B3tca	65	7.1	1.36	.96	.098	--	.88	--	--	--	--	--
172	20	RC-43	2C1ca	98	13.	0	.03	.033	--	.32	--	--	--	--	--
173	20	RC-43	3C2ca	+200	35.	0	0	.019	--	.42	--	--	--	--	--
174	120	RC-27	A	6	2.9	.40	.86	--	--	.61	--	--	--	--	--
175	120	RC-27	2B1t	11	1.4	.49	.46	--	--	0	--	--	--	--	--
176	120	RC-27	2B2t	19	1.5	.30	1.3	--	--	.02	--	--	--	--	--
177	120	RC-27	3B3ca	34	6.7	.30	.23	--	--	2.8	--	--	--	--	--
178	120	RC-27	3C1ca	74	23.	0	2.1	--	--	5.1	--	--	--	--	--
179	120	RC-27	4C2ca	147	43.	0	0	--	--	7.2	--	--	--	--	--
180	120	RC-27	5C3ca	+225	22.	0	0	--	--	1.9	--	--	--	--	--
181	415	RC-23	A	3	.94	.61	.16	.13	.0008	0	.12	0	.083	.33	.059
182	415	RC-23	B1tca	7	1.3	1.1	.27	.084	.0006	.03	.10	.011	.13	.23	.071
183	415	RC-23	B2tca	14	1.1	.72	.39	.089	.0010	1.4	.15	.007	.15	.23	.15
184	415	RC-23	B3tca	29	4.1	1.2	.60	.14	.0042	4.3	.37	.022	.079	.43	.22
185	415	RC-23	2K	60	13.	-.02	0	.027	.0033	9.9	.28	.010	.063	.26	.43
186	415	RC-23	3C1ca	121	9.9	2.4	1.8	.029	.0013	1.1	.49	0	.19	.67	1.0
187	415	RC-23	3C2ca	170	11.	.75	.33	.015	--	4.3	.16	0	.044	.18	.36
188	415	RC-23	4C3ca	226	22.	0	0	.012	--	1.3	--	--	--	--	--
189	415	RC-23	5C4ca	255	9.1	0	0	.005	--	2.4	--	--	--	--	--
190	415	RC-23	5C5ca	310	15.6	0	0	.018	--	1.3	--	--	--	--	--
191	415	RC-23	5C6ca	+320	--	--	--	--	--	--	--	--	--	--	--
192	600	RC-24	A	4	1.3	1.0	1.1	.13	.0016	0	.20	.033	.33	.89	.22
193	600	RC-24	B1t	9	1.6	1.5	1.7	.17	.0013	0	.48	.048	.46	1.1	.31
194	600	RC-24	B2tca	19	2.2	2.1	3.2	.20	.0037	.19	.88	.046	1.4	1.7	.65
195	600	RC-24	B3tca	30	2.1	2.1	1.3	.13	.0045	3.3	.78	.049	.46	.61	.53
196	600	RC-24	K	45	2.2	.79	.95	.13	.0013	6.9	.42	.037	.22	.55	.59
197	600	RC-24	2C1ca	62	5.3	.38	.50	.025	.0011	1.3	.19	.011	.042	.34	.46
198	600	RC-24	2C2ca	87	7.8	.29	0	.013	.0001	.20	--	--	--	--	--
199	600	RC-24	2C3ca	+300	73.	0	0	0	--	1.9	--	--	--	--	--
200	945	RC-25	Aca	4	1.6	.13	.07	--	--	.14	--	--	--	--	--
201	945	RC-25	B1tca	9	1.3	-.18	.18	--	--	.72	--	--	--	--	--
202	945	RC-25	B2tca	15	1.5	-.14	.25	--	--	1.5	--	--	--	--	--
203	945	RC-25	B3tca	25	2.0	.23	.41	--	--	2.9	--	--	--	--	--
204	945	RC-25	2K	49	5.7	.34	.39	--	--	10.	--	--	--	--	--
205	945	RC-25	2C1ca	65	6.6	.37	.08	--	--	4.8	--	--	--	--	--
206	945	RC-25	2C2ca	91	9.2	.10	0	--	--	1.3	--	--	--	--	--
207	945	RC-25	3C3ca	+130	33.	0	0	--	--	.60	--	--	--	--	--
208	945	RC-44	Aca	6	1.9	.40	.67	.14	.0012	.19	.48	.12	.45	.12	.19
209	945	RC-44	B1tca	13	1.9	.24	1.4	.18	.0020	.43	.44	.12	.23	1.4	.19
210	945	RC-44	B21tca	19	.69	.48	.49	.071	.0009	.50	.21	.026	.18	.31	.12
211	945	RC-44	B22tca	27	2.2	2.0	1.2	.16	.0025	2.6	.11	.060	.22	.66	.45
212	945	RC-44	B31tca	45	2.3	1.7	1.0	.21	.0029	4.8	.46	.066	.21	.16	.42
213	945	RC-44	2B32tca	86	9.2	2.2	.39	.059	.0011	1.8	.10	.017	.033	.27	.43
214	945	RC-44	2Cca	+120	7.6	.65	0	.019	.0003	.26	.006	.004	.006	.072	.098

Supplementary table 7, part 1. Horizon weights of sand, silt, clay, carbon, organic phosphorus, $CaCO_3$, and clay minerals--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	horizon weight (g/cm^2/horizon column)										
					Sand	Silt	Clay	Carbon	Organic phosphorus	$CaCO_3$	Kaolinite	Chlorite	Mica	Mixed-layer smectite-illite	Smectite
215	2,000	RC-26A	A	6	2.9	1.0	.07	.12	.0009	0	.13	.067	.28	.19	.082
216	2,000	RC-26A	B1t	11	1.8	.23	.60	.11	.0008	0	.28	.023	.12	.61	.14
217	2,000	RC-26A	B21t	20	4.6	1.3	2.0	.27	.0027	0	.53	.067	.50	1.40	.83
218	2,000	RC-26A	B22tca	29	3.9	.67	1.3	.23	.0016	.11	.30	.20	.79	.27	.92
219	2,000	RC-26A	B3tca	40	2.8	1.2	1.1	.14	.0032	3.0	--	--	--	--	--
220	2,000	RC-26A	2K	68	6.9	.78	1.0	.053	.0062	11.	.029	.014	.058	.65	.71
221	2,000	RC-26A	2C1ca	145	25.	2.8	.40	.052	.0028	6.0	.025	0	.025	.56	.61
222	2,000	RC-26A	2C2ca	247	62.	.71	0	.007	0	1.4	--	--	--	--	--
223	2,000	RC-26A	3C3ca	295	35.	0	0	.004	.0025	.26	--	--	--	--	--
224	2,000	RC-26B	A	5	3.7	.18	.19	--	--	0	--	--	--	--	--
225	2,000	RC-26B	B1t	10	2.4	-.05	.76	--	--	0	--	--	--	--	--
226	2,000	RC-26B	B2t	16	3.2	.04	.78	--	--	0	--	--	--	--	--
227	2,000	RC-26B	B31tca	25	3.8	1.3	1.4	--	--	2.2	--	--	--	--	--
228	2,000	RC-26B	B32tca	36	3.8	.64	.68	--	--	3.9	--	--	--	--	--
229	2,000	RC-26B	2K	48	4.6	.35	.35	--	--	4.7	--	--	--	--	--
230	2,000	RC-26B	2C1ca	88	18.	1.1	.57	--	--	9.2	--	--	--	--	--
231	2,000	RC-26B	2C2ca	+170	38.	1.2	0	--	--	4.2	--	--	--	--	--

Supplementary table 7, part 2. Horizon weights of major oxides plus zirconium in the less-than-2-mm fraction

[Analyst: M. C. Reheis, U. S. Geological Survey. --, not measured; tr, trace]

Methods

Horizon weights for element oxides are calculated using the first term in equation 2 given in supplementary table 7, part 1. Parent material amounts are not subtracted.

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	horizon weight (g/cm^2/horizon in less-than-2 mm fraction)									
					SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	ZrO_2
1	modern	RC-R	channel gravel		--	--	--	--	--	--	--	--	--	--
2	modern	RC-M	channel gravel		--	--	--	--	--	--	--	--	--	--
			Mountain-front chronosequence											
3	7	RC-38	A1	9	5.0	0.86	0.15	0.051	0.13	0.35	0.15	0.013	0.002	0.001
4	7	RC-38	2A31	22	7.1	1.3	.26	.088	.19	.48	.25	.022	.003	.002
5	7	RC-38	2A32	33	6.2	1.1	.22	.078	.17	.40	.19	.021	.003	.002
6	7	RC-38	2AC	46	6.6	1.1	.28	.080	.17	.48	.21	.023	.003	.002
7	7	RC-38	3C1ox	85	8.2	1.4	.24	.091	.20	.53	.25	.023	.002	.002
8	7	RC-38	3C2ox	+120	9.0	1.7	.29	.11	.24	.54	.27	.032	.003	.003
9	20	RC-21	A	5	4.6	.87	.23	.061	.10	.23	.16	.026	.004	.002
10	20	RC-21	B1t	12	7.5	1.5	.38	.11	.16	.38	.27	.043	.006	.003
11	20	RC-21	B2t	25	11.	2.2	.58	.17	.22	.45	.41	.069	.009	.005
12	20	RC-21	2B3t	38	11.	2.1	.50	.15	.24	.55	.35	.048	.006	.004
13	20	RC-21	3C1ox	73	7.2	1.3	.26	.083	.19	.48	.23	.024	.003	.001
14	20	RC-21	3C2ox	+110	7.1	1.4	.24	.078	.21	.45	.21	.022	.002	.002
15	20	RC-15	A	8	--	--	--	--	--	--	--	--	--	--
16	20	RC-15	2B2t	23	--	--	--	--	--	--	--	--	--	--
17	20	RC-15	2B3	43	--	--	--	--	--	--	--	--	--	--
18	20	RC-15	2Cox	+68	--	--	--	--	--	--	--	--	--	--

Supplementary table 7, part 2. Horizon weights of major oxides plus zirconium in the less-than-2-mm fraction--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	horizon weight (g/cm^2/horizon in less-than-2 mm fraction)									
					SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	ZrO_2
19	120	RC-31	A1	8	4.2	.88	.22	.072	.12	.19	.16	.023	.004	.001
20	120	RC-31	A3	19	6.9	1.4	.34	.10	.17	.36	.29	.033	.006	.002
21	120	RC-31	B1t	32	7.0	1.4	.42	.13	.15	.34	.27	.041	.007	.003
22	120	RC-31	B21t	54	18.	3.7	.91	.29	.43	.85	.70	.092	.012	.006
23	120	RC-31	B22t	81	18.	4.5	1.2	.31	.55	.93	.64	.11	.011	.006
24	120	RC-31	2B31t	123	30.	7.2	1.9	.55	1.2	2.0	.78	.16	.025	.008
25	120	RC-31	2B32t	145	6.8	1.4	.43	.15	.25	.41	.19	.034	.005	.002
26	120	RC-31	2Cox	+200	21.	4.6	1.3	.47	.81	1.3	.69	.10	.016	.005
27	120	RC-17	A	9	--	--	--	--	--	--	--	--	--	--
28	120	RC-17	B1t	20	--	--	--	--	--	--	--	--	--	--
29	120	RC-17	B2t	31	--	--	--	--	--	--	--	--	--	--
30	120	RC-17	B31t	50	--	--	--	--	--	--	--	--	--	--
31	120	RC-17	2B32t	122	--	--	--	--	--	--	--	--	--	--
32	120	RC-17	2Cox	+136	--	--	--	--	--	--	--	--	--	--
33	415	RC-30	A1	9	5.6	1.2	.28	.096	.20	.28	.22	.027	.005	.002
34	415	RC-30	A3	17	6.1	1.3	.29	.099	.18	.33	.23	.025	.005	.001
35	415	RC-30	B1t	29	8.9	1.9	.55	.19	.26	.44	.33	.049	.008	.003
36	415	RC-30	B2t	53	14.	3.2	.91	.32	.43	.76	.50	.075	.009	.003
37	415	RC-30	2B31t	81	17.	4.2	.94	.31	.55	.98	.60	.074	.011	.004
38	415	RC-30	2B32t	170	54.	12.	3.2	1.1	1.7	3.0	1.7	.27	.055	.012
39	415	RC-30	2Cox	+250	16.	3.5	.95	.40	.56	.85	.59	.076	.010	.003
40	600	RC-29	A1	9	2.3	.50	.15	.055	.080	.11	.085	.015	.002	.001
41	600	RC-29	A3	18	3.7	.84	.24	.090	.13	.20	.15	.022	.004	.001
42	600	RC-29	B1t	30	8.2	1.9	.57	.21	.28	.42	.30	.053	.009	.002
43	600	RC-29	B2t	50	9.3	2.1	.61	.26	.32	.50	.33	.056	.008	.003
44	600	RC-29	2B31t	79	14.	3.2	1.2	.36	.52	.72	.44	.10	.016	.004
45	600	RC-29	3B32t	167	60.	13.	5.1	2.3	2.6	3.2	1.9	.44	.069	.019
46	600	RC-29	3Cox	+260	41.	8.9	2.7	1.3	1.5	2.2	1.3	.22	.038	.008
47	600	RC-16	A	27	--	--	--	--	--	--	--	--	--	--
48	600	RC-16	B1t	47	--	--	--	--	--	--	--	--	--	--
49	600	RC-16	2B2t	72	--	--	--	--	--	--	--	--	--	--
50	600	RC-16	2B3t	127	--	--	--	--	--	--	--	--	--	--
51	600	RC-16	2Cox	+197	--	--	--	--	--	--	--	--	--	--
52	2,000	RC-28	A	7	--	--	--	--	--	--	--	--	--	--
53	2,000	RC-28	B1t	11	--	--	--	--	--	--	--	--	--	--
54	2,000	RC-28	B2t	17	3.9	.96	.23	.062	.11	.22	.17	.021	.003	.002
55	2,000	RC-28	2B31t	47	--	--	--	--	--	--	--	--	--	--
56	2,000	RC-28	2B32t	141	--	--	--	--	--	--	--	--	--	--
57	2,000	RC-28	2Cox	+270	--	--	--	--	--	--	--	--	--	--
58	2,000	RC-14	A	17	12.	2.5	.64	.17	.27	.50	.52	.071	.013	.003
59	2,000	RC-14	B1t	32	13.	2.8	.75	.21	.29	.48	.48	.080	.012	.004
60	2,000	RC-14	B2t	44	11.	2.4	.60	.18	.27	.50	.38	.061	.008	.003
61	2,000	RC-14	2B31t	84	19.	4.4	1.2	.40	.61	1.0	.68	.099	.017	.004
62	2,000	RC-14	3B32t	144	28.	6.0	1.5	.56	.88	1.5	.85	.12	.021	.004
63	2,000	RC-14	3Cox	+164	7.8	1.7	.35	.11	.25	.47	.31	.035	.004	.002
					Transition chronosequence									
64	7	RC-40	A	13	--	--	--	--	--	--	--	--	--	--
65	7	RC-40	Bs	46	--	--	--	--	--	--	--	--	--	--
66	7	RC-40	2C1ox	65	--	--	--	--	--	--	--	--	--	--
67	7	RC-40	2C2ox	310	--	--	--	--	--	--	--	--	--	--
68	7	RC-42	A1	6	2.9	.45	.11	.039	.067	.14	.095	.013	.002	.001
69	7	RC-42	A3	37	10.	1.7	.41	.15	.24	.50	.34	.046	.007	.003
70	7	RC-42	2Bs	55	17.	2.9	.69	.25	.39	.83	.53	.077	.009	.006
71	7	RC-42	3Bb	73	9.9	1.8	.44	.15	.25	.47	.33	.050	.006	.004
72	7	RC-42	3Coxb	+200	45.	8.5	1.4	.59	1.4	2.9	1.4	.13	.021	.008

Supplementary table 7, part 2. Horizon weights of major oxides plus zirconium in the less-than-2-mm fraction--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	horizon weight (g/cm^2/horizon in less-than-2 mm fraction)									
					SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	ZrO_2
73	20	RC-22	A	5	--	--	--	--	--	--	--	--	--	--
74	20	RC-22	B1t	25	--	--	--	--	--	--	--	--	--	--
75	20	RC-22	B2t	43	--	--	--	--	--	--	--	--	--	--
76	20	RC-22	2B3t	57	--	--	--	--	--	--	--	--	--	--
77	20	RC-22	2C1ox	78	--	--	--	--	--	--	--	--	--	--
78	20	RC-22	2C2ox	175	--	--	--	--	--	--	--	--	--	--
79	20	RC-22	3Cca	197	--	--	--	--	--	--	--	--	--	--
80	20	RC-22	3Cn	+240	--	--	--	--	--	--	--	--	--	--
81	120	RC-12	A	9	--	--	--	--	--	--	--	--	--	--
82	120	RC-12	B1t	17	--	--	--	--	--	--	--	--	--	--
83	120	RC-12	B2t	39	--	--	--	--	--	--	--	--	--	--
84	120	RC-12	2B3t	62	--	--	--	--	--	--	--	--	--	--
85	120	RC-12	2Cox	+122	--	--	--	--	--	--	--	--	--	--
86	120	RC-32	Ap	21	--	--	--	--	--	--	--	--	--	--
87	120	RC-32	2B2tca	37	7.0	1.6	.49	.15	.19	.27	.27	.046	.006	.003
88	120	RC-32	2B3tca	70	--	--	--	--	--	--	--	--	--	--
89	120	RC-32	3Cca	+80	--	--	--	--	--	--	--	--	--	--
90	120	RC-41	A	8	4.7	.67	.20	.050	.088	.16	.14	.022	.004	.002
91	120	RC-41	B1t	17	6.4	1.0	.30	.071	.10	.22	.21	.038	.005	.003
92	120	RC-41	B2t	28	6.9	1.4	.44	.11	.11	.20	.24	.042	.004	.003
93	120	RC-41	2B31t	51	10.	2.1	.50	.14	.22	.48	.35	.043	.005	.003
94	120	RC-41	2B32t	65	6.3	1.3	.32	.11	.17	.33	.20	.025	.004	.002
95	120	RC-41	2Cox	+100	8.6	1.7	.28	.088	.23	.56	.28	.019	.004	.001
96	415	RC-11	A	9	--	--	--	--	--	--	--	--	--	--
97	415	RC-11	B2t	20	--	--	--	--	--	--	--	--	--	--
98	415	RC-11	B3t	50	--	--	--	--	--	--	--	--	--	--
99	415	RC-11	2C1ca	100	--	--	--	--	--	--	--	--	--	--
100	415	RC-11	2C2ca	+180	--	--	--	--	--	--	--	--	--	--
101	415	RC-37	A	6	--	--	--	--	--	--	--	--	--	--
102	415	RC-37	B1t	18	--	--	--	--	--	--	--	--	--	--
103	415	RC-37	B2tca	45	--	--	--	--	--	--	--	--	--	--
104	415	RC-37	B3tca/K	63	--	--	--	--	--	--	--	--	--	--
105	415	RC-37	2C1ca	109	--	--	--	--	--	--	--	--	--	--
106	415	RC-37	3C2ca	230	--	--	--	--	--	--	--	--	--	--
107	415	RC-37	3C3ca	+240	--	--	--	--	--	--	--	--	--	--
108	600	RC-34	A1	8	--	--	--	--	--	--	--	--	--	--
109	600	RC-34	A3	14	--	--	--	--	--	--	--	--	--	--
110	600	RC-34	B1t	22	--	--	--	--	--	--	--	--	--	--
111	600	RC-34	B2t	37	--	--	--	--	--	--	--	--	--	--
112	600	RC-34	2B3t/ca	54	--	--	--	--	--	--	--	--	--	--
113	600	RC-34	3Cox/ca	89	--	--	--	--	--	--	--	--	--	--
114	600	RC-34	3C1ca	160	--	--	--	--	--	--	--	--	--	--
115	600	RC-34	3C2ca	+210	--	--	--	--	--	--	--	--	--	--
116	600	RC-35	A	5	--	--	--	--	--	--	--	--	--	--
117	600	RC-35	B1t	10	--	--	--	--	--	--	--	--	--	--
118	600	RC-35	B2tca	18	--	--	--	--	--	--	--	--	--	--
119	600	RC-35	B3tca	32	--	--	--	--	--	--	--	--	--	--
120	600	RC-35	2C1ca	54	--	--	--	--	--	--	--	--	--	--
121	600	RC-35	2C2ca	135	--	--	--	--	--	--	--	--	--	--
122	600	RC-35	2C3ca	225	--	--	--	--	--	--	--	--	--	--
123	600	RC-35	2C4ca	+235	--	--	--	--	--	--	--	--	--	--
124	945	RC-6	A	13	--	--	--	--	--	--	--	--	--	--
125	945	RC-6	B1t	30	--	--	--	--	--	--	--	--	--	--
126	945	RC-6	B2t	46	--	--	--	--	--	--	--	--	--	--
127	945	RC-6	2C1ca	96	--	--	--	--	--	--	--	--	--	--
128	945	RC-6	2C2ca	+126	--	--	--	--	--	--	--	--	--	--

Supplementary table 7, part 2. Horizon weights of major oxides plus zirconium in the less-than-2-mm fraction--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	horizon weight (g/cm^2/horizon in less-than-2 mm fraction)									
					SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	ZrO_2
129	945	RC-36	A	7	--	--	--	--	--	--	--	--	--	--
130	945	RC-36	B1t	16	--	--	--	--	--	--	--	--	--	--
131	945	RC-36	B2tca	25	--	--	--	--	--	--	--	--	--	--
132	945	RC-36	B3tca	35	--	--	--	--	--	--	--	--	--	--
133	945	RC-36	K	53	--	--	--	--	--	--	--	--	--	--
134	945	RC-36	2C1ca	80	--	--	--	--	--	--	--	--	--	--
135	945	RC-36	3C2ca	103	--	--	--	--	--	--	--	--	--	--
136	945	RC-36	3C3ca	173	--	--	--	--	--	--	--	--	--	--
137	945	RC-36	3C4ca	200	--	--	--	--	--	--	--	--	--	--
138	945	RC-36	4C5ca	227	--	--	--	--	--	--	--	--	--	--
139	945	RC-36	4C6ca	+255	--	--	--	--	--	--	--	--	--	--
140	2,000	RC-33	A1	9	--	--	--	--	--	--	--	--	--	--
141	2,000	RC-33	A3	16	--	--	--	--	--	--	--	--	--	--
142	2,000	RC-33	B1t	24	--	--	--	--	--	--	--	--	--	--
143	2,000	RC-33	B2t	43	--	--	--	--	--	--	--	--	--	--
144	2,000	RC-33	2B3t/ca	58	--	--	--	--	--	--	--	--	--	--
145	2,000	RC-33	2K1	58	--	--	--	--	--	--	--	--	--	--
146	2,000	RC-33	2K2	92	--	--	--	--	--	--	--	--	--	--
147	2,000	RC-33	3C1ca	180	--	--	--	--	--	--	--	--	--	--
148	2,000	RC-33	3C2ca	+220	--	--	--	--	--	--	--	--	--	--
149	2,000	RC-8	A	8	--	--	--	--	--	--	--	--	--	--
150	2,000	RC-8	B2t	22	--	--	--	--	--	--	--	--	--	--
151	2,000	RC-8	2B3tca	72	--	--	--	--	--	--	--	--	--	--
152	2,000	RC-8	2K	112	--	--	--	--	--	--	--	--	--	--
153	2,000	RC-8	2Cca	+162	--	--	--	--	--	--	--	--	--	--
Basin chronosequence														
154	7	RC-46A	Ap	20	--	--	--	--	--	--	--	--	--	--
155	7	RC-46A	ACca	40	--	--	--	--	--	--	--	--	--	--
156	7	RC-46A	2Cgca	70	--	--	--	--	--	--	--	--	--	--
157	7	RC-46A	2Cox	98	--	--	--	--	--	--	--	--	--	--
158	7	RC-46A	3Cn	+150	--	--	--	--	--	--	--	--	--	--
159	7	RC-46B	Apca	28	26.	4.5	1.4	.70	1.3	.51	.84	.20	.022	.018
160	7	RC-46B	2Cca	60	19.	2.6	.93	.50	1.2	.42	.53	.14	.014	.025
161	7	RC-46B	3Cn	+150	17.	3.0	.79	.33	.69	.68	.53	.092	.012	.010
154	20	RC-20	A	9	9.9	1.5	.44	.12	.18	.32	.30	.050	.007	.004
155	20	RC-20	2B1t	15	6.7	1.2	.40	.11	.13	.21	.21	.037	.006	.003
156	20	RC-20	2B2tca	32	11.	2.0	.66	.18	.26	.42	.34	.052	.009	.004
157	20	RC-20	2B3tca	50	11.	1.6	.50	.12	.25	.43	.30	.041	.008	.004
158	20	RC-20	3C1ca	130	27.	3.5	1.1	.26	.70	.98	.67	.085	.021	.007
159	20	RC-20	3C2ca	+330	38.	7.5	1.5	.55	1.2	2.1	1.3	.11	.022	.007
168	20	RC-43	A	18	--	--	--	--	--	--	--	--	--	--
169	20	RC-43	B1t	33	--	--	--	--	--	--	--	--	--	--
170	20	RC-43	B2t	44	--	--	--	--	--	--	--	--	--	--
171	20	RC-43	2B3tca	65	--	--	--	--	--	--	--	--	--	--
172	20	RC-43	2C1ca	98	--	--	--	--	--	--	--	--	--	--
173	20	RC-43	3C2ca	+200	--	--	--	--	--	--	--	--	--	--
174	120	RC-27	A	6	5.0	.87	.29	.15	.47	.12	.18	.036	.004	.003
175	120	RC-27	2B1t	11	2.1	.37	.13	.046	.076	.052	.073	.015	.002	.001
176	120	RC-27	2B2t	19	2.5	.58	.22	.071	.084	.060	.10	.022	.003	.001
177	120	RC-27	2B3ca	34	11.	1.9	.64	.38	2.6	.25	.33	.074	.008	.006
178	120	RC-27	3C1ca	74	39.	6.5	2.1	1.4	5.7	.88	1.2	.27	.025	.026
179	120	RC-27	4C2ca	147	65.	11.	3.5	3.3	7.5	1.8	2.1	.44	.046	.038
180	120	RC-27	5C3ca	+225	20.	3.0	1.1	.55	1.9	.58	.57	.098	.017	.006

Supplementary table 7, part 2. Horizon weights of major oxides plus zirconium in the less-than-2-mm fraction--Continued

No.	Age (ka)	Sample number	Horizon	Basal depth (cm)	horizon weight (g/cm^2/horizon in less-than-2 mm fraction)									
					SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	MnO	ZrO_2
181	415	RC-23	A	3	2.2	.37	.11	.038	.063	.062	.081	.014	.002	.001
182	415	RC-23	B1tca	7	2.4	.40	.11	.040	.074	.074	.086	.015	.002	.001
183	415	RC-23	B2tca	14	2.1	.39	.11	.045	.22	.067	.076	.014	.002	.001
184	415	RC-23	B3tca	29	4.7	.93	.21	.11	1.8	.21	.15	.026	.003	.002
185	415	RC-23	2K	60	11.	2.0	.31	.28	4.5	.54	.42	.034	.004	.003
186	415	RC-23	3C1ca	121	10.	2.0	.54	.38	.81	.42	.34	.053	.051	.004
187	415	RC-23	3C2ca	170	9.5	1.7	.39	.31	.42	.38	.28	.038	.011	.004
188	415	RC-23	4C3ca	226	21.	3.9	.75	.77	1.9	.97	.67	.088	.012	.007
189	415	RC-23	5C4ca	255	7.3	1.4	.27	.17	.29	.36	.24	.023	.003	.003
190	415	RC-23	5C5ca	310	--	--	--	--	--	--	--	--	--	--
191	415	RC-23	5C6ca	+320	--	--	--	--	--	--	--	--	--	--
192	600	RC-24	A	4	3.3	.66	.23	.076	.080	.082	.13	.027	.003	.002
193	600	RC-24	B1t	9	4.5	.92	.32	.11	.11	.11	.17	.036	.004	.002
194	600	RC-24	B2tca	19	7.7	1.7	.59	.23	.29	.18	.29	.064	.007	.004
195	600	RC-24	B3tca	30	6.0	1.2	.39	.28	1.9	.15	.22	.047	.005	.003
196	600	RC-24	K	45	3.9	.76	.23	.34	3.8	.12	.13	.029	.002	.002
197	600	RC-24	2C1ca	62	5.1	1.0	.26	.26	.90	.22	.17	.029	.003	.002
198	600	RC-24	2C2ca	87	5.8	1.1	.46	.21	.26	.28	.18	.059	.005	.003
199	600	RC-24	2C3ca	+300	54.	9.4	2.2	.83	1.6	2.7	1.8	.25	.027	.024
200	945	RC-25	Aca	4	--	--	--	--	--	--	--	--	--	--
201	945	RC-25	B1tca	9	--	--	--	--	--	--	--	--	--	--
202	945	RC-25	B2tca	15	2.2	.43	.15	.090	.081	.088	.081	.018	.002	.001
203	945	RC-25	B3tca	25	--	--	--	--	--	--	--	--	--	--
204	945	RC-25	2K	49	--	--	--	--	--	--	--	--	--	--
205	945	RC-25	2C1ca	65	--	--	--	--	--	--	--	--	--	--
206	945	RC-25	2C2ca	91	--	--	--	--	--	--	--	--	--	--
207	945	RC-25	3C3ca	+130	--	--	--	--	--	--	--	--	--	--
208	945	RC-44	Aca	6	3.6	.63	.21	.083	.18	.085	.13	.025	.003	.001
209	945	RC-44	B1tca	13	4.2	.84	.29	.12	.31	.089	.17	.032	.003	.002
210	945	RC-44	B21tca	19	1.7	.33	.11	.063	.29	.037	.064	.013	.001	.001
211	945	RC-44	B22tca	27	4.1	.76	.24	.33	1.3	.11	.14	.030	.003	.002
212	945	RC-44	B31tca	45	3.9	.77	.25	.28	2.4	.12	.14	.030	.003	.001
213	945	RC-44	2B32tca	86	8.7	1.5	.49	.64	.98	.33	.29	.052	.006	.003
214	945	RC-44	2Cca	+120	6.1	.94	.29	.37	.26	.21	.18	.029	.003	.002
215	2,000	RC-26A	A	6	4.5	.71	.16	.050	.084	.15	.15	.024	.004	.002
216	2,000	RC-26A	B1t	11	3.0	.56	.15	.050	.061	.096	.11	.019	.002	.001
217	2,000	RC-26A	B21t	20	8.5	1.6	.43	.16	.17	.25	.33	.054	.007	.003
218	2,000	RC-26A	B22tca	29	6.6	1.2	.31	.13	.19	.22	.22	.041	.005	.002
219	2,000	RC-26A	B3tca	40	4.5	.84	.21	.20	1.6	.15	.15	.026	.003	.002
220	2,000	RC-26A	2K	68	6.8	1.2	.23	1.0	5.0	.32	.25	.027	.004	.001
221	2,000	RC-26A	2C1ca	145	20.	3.5	.51	1.6	2.7	1.0	.70	.065	.008	.004
222	2,000	RC-26A	2C2ca	247	46.	8.0	.98	1.1	1.7	2.5	1.5	.084	.012	.006
223	2,000	RC-26A	3C3ca	295	--	--	--	--	--	--	--	--	--	--
224	2,000	RC-26B	A	5	--	--	--	--	--	--	--	--	--	--
225	2,000	RC-26B	B1t	10	--	--	--	--	--	--	--	--	--	--
226	2,000	RC-26B	B2tca	16	5.3	.99	.29	.12	.14	.15	.20	.038	.003	.003
227	2,000	RC-26B	B31tca	25	--	--	--	--	--	--	--	--	--	--
228	2,000	RC-26B	B32tca	36	--	--	--	--	--	--	--	--	--	--
229	2,000	RC-26B	2K	48	--	--	--	--	--	--	--	--	--	--
230	2,000	RC-26B	2C1ca	88	--	--	--	--	--	--	--	--	--	--
231	2,000	RC-26B	2C2ca	+170	--	--	--	--	--	--	--	--	--	--

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