Holocene Alpine Soils in Gneissic Cirque Deposits, Colorado Front Range

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Chapter E

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By P.W. BIRKELAND, R.M. BURKE, and R.R. SHROBA

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SOIL CHRONOSEQUENCES IN THE WESTERN UNITED STATES

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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 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; the 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 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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Holocene Alpine Soils in Gneissic Cirque Deposits, Colorado Front Range

By P.W. Birkeland,[1] R.M. Burke,[2] *and* R.R. Shroba

ABSTRACT

Study of a chronosequence of alpine soils in the Colorado Front Range suggests a moderately rapid rate of soil formation during the Holocene. Soil parent materials in this study include glacial and periglacial deposits named Gannett Peak (100-350 yr), Audubon (950-2,400 yr), Triple Lakes (3,000-5,200 yr), and Satanta Peak (10,000-12,000 yr). Soil morphology and chemistry vary in a predictable manner with increasing age. The post-Gannett Peak soil has a very thin, weakly developed A/Cox profile; the post-Audubon soil has a thicker, better developed A/AC/Cox profile; the post-Triple Lakes soil has an A/Bw/Cox profile; and post-Satanta Peak soils have A/Bw (or Bt)/Cox profiles. The two youngest soils are classified as Pergelic Cryorthents, the post-Triple Lakes soil is either a Pergelic Cryumbrept or Pergelic Cryoboroll. The best developed of the post-Satanta Peak soils are either Argic Pergelic Cryoborolls or Pergelic Cryoboralfs. Airborne dust seems to have had an influence on the texture of the surface horizons of the post-Triple Lakes and post-Satanta Peak soils, and may account for some of the translocated clay in the Bt horizons of the post-Satanta Peak soils.

Soil development trends with increasing age include increasing amounts of organic carbon, total nitrogen, organic-bound phosphorus, clay, extractable iron and aluminum, and higher cation exchange capacity. Loss of acid-extractable calcium-bound phosphorus with time suggests a moderately intense leaching environment. Calcium is the dominant exchangeable cation in all soils, and magnesium is present as an exchangeable cation only in the post-Triple Lakes and post-Satanta Peak soils. The clay mineralogy is difficult to interpret, but the main trends with time are the depletion and (or) dilution of kaolinite, smectite, and mica, and the formation and (or) addition of 1-1.4 nm mixed-layer clays.

Both the field and laboratory data suggest a moderately rapid rate of development for soils in the alpine of the Colorado Front Range compared to those at lower elevations, in spite of the cold climate.

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INTRODUCTION

Soil formation is moderately rapid in the higher mountain ranges of the western United States, as compared to those at lower elevations. One such area is the Colorado Front Range (Shroba and Birkeland, 1983). The main objective of this report is to document soil development in the alpine of the Colorado Front Range by utilizing soil morphology; physical, chemical, and mineralogical data; and various soil development indices. Other objectives are (1) to compare our age assignments and soil-horizon designations with those of previous workers, (2) to determine the variability and reproducibility of the field and laboratory data for the post-Satanta Peak soils, and (3) to evaluate the usefulness of some color and soil-profile indices as an indication of soil age in an alpine environment.

The soils studied are in Arapaho cirque, a small alpine basin in the Indian Peaks area of the Colorado Front Range (fig. 1). Arapaho Glacier, the largest glacier in Colorado, lies against the headwall in the western part of the cirque. The cirque walls are steep and rise about 150 to 350 m. The soils have formed from Holocene and very latest Pleistocene deposits downvalley of the glacier at altitudes between 3,450 and 3,700 m.

Mahaney (1974) did the initial quantitative work on the soils in Arapaho cirque and vicinity. Subsequent, detailed soil investigations have been conducted in the study area and (or) in nearby cirques and valleys by Shroba (1977; Shroba and Birkeland, 1983), Benedict (1981, 1985), Burns (1980), Dixon (1983, 1986), Albino (1984), and Litaor (1987). This report provides additional morphological, chemical, and mineralogical data for the soils in Arapaho cirque.

Acknowledgments.—J.W. Harden helped describe the soils in the field. Discussions with numerous people have been helpful to us over the many years that we have worked in the cirques of the Colorado Front Range. These people include J.T. Andrews, J.B. Benedict, S.F. Burns, P.E. Carrara, T. Carroll, D.R. Crandell, P.T. Davis, W.C. Mahaney, and D.R. Mullineaux. R. Kihl of the University of Colorado analyzed some of the samples from soil CO8. R. Bruce and D. Geary assisted in the field, and students in

Birkeland's 1982 soils class at the University of Colorado helped calculate some of the indices. This project was funded by the U.S. Geological Survey Soil Correlation and Dating Project, coordinated by the late D.E. Marchand and M.N. Machette. We are grateful to J.B. Benedict, A.J. Busacca, and P.E. Carrara for their thoughtful reviews of this manuscript.

ENVIRONMENTAL FACTORS

Pedologists recognize five main factors that define the state of the soil system (Jenny, 1980). These are parent material, time (duration of soil development), climate, vegetation, and topography.

Parent Materials

The deposits from which the soils are formed include till and rock-glacier debris. These deposits have a high boulder content (commonly greater than 50 percent by volume) and a sandy matrix. Deposits older than about 1,000 years usually have a loamy surface layer that makes up the upper part of the soil. This material has been considered to be eolian in origin (Benedict, 1973, 1981; Mahaney, 1974; Birkeland and

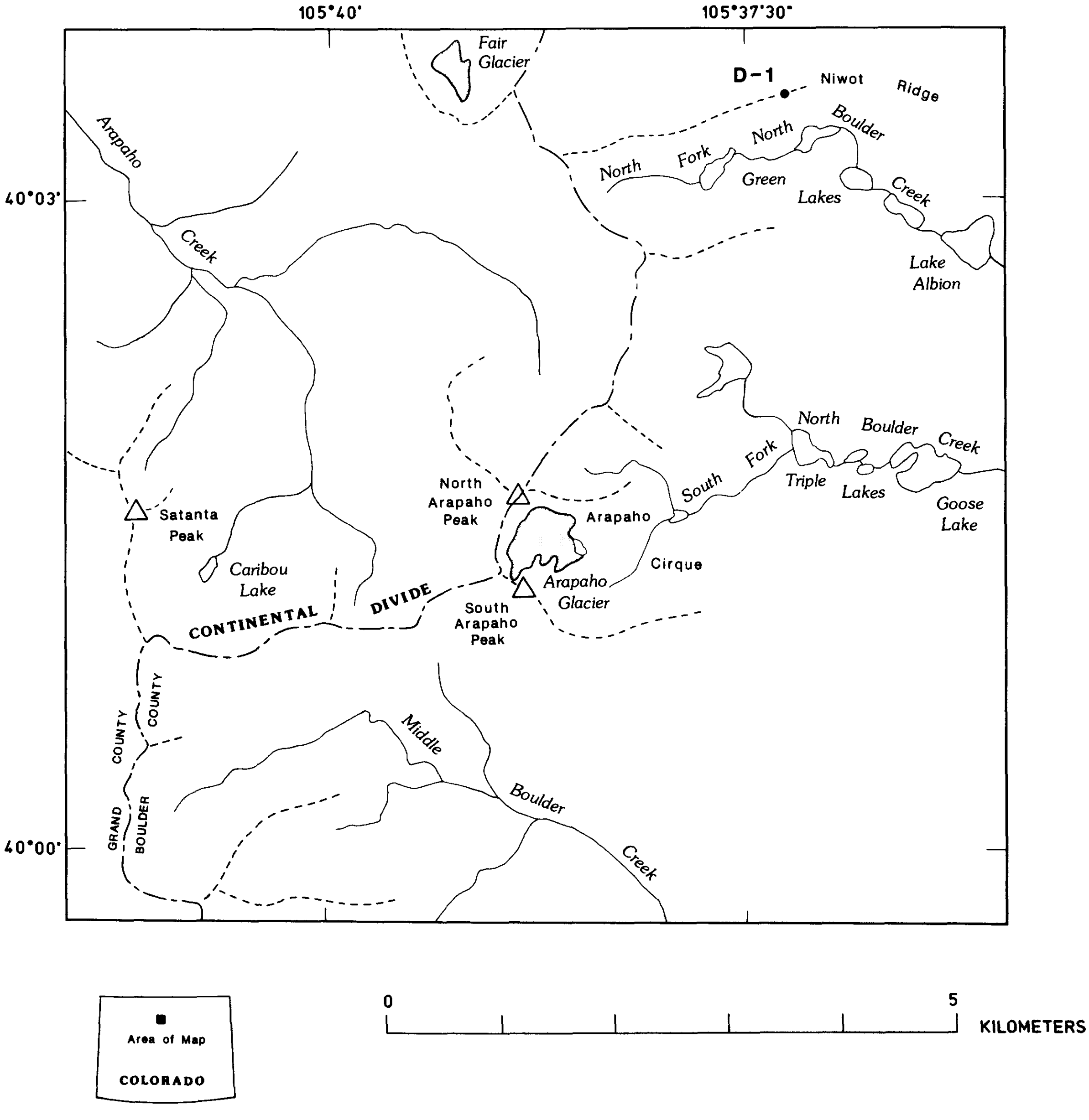

Figure 1. Generalized map of study area. Short dashed lines indicate prominent ridge crests; triangles denote peaks. Location of meteorological station D-1 is approximate. Grid pattern indicates extent of glaciers.

Shroba, 1974; Shroba, 1977; Burns, 1980; Thorn and Darmody, 1980, 1985; Burns and Tonkin, 1982; Shroba and Birkeland, 1983; and Litaor, 1987). Dixon (1983, 1986) also recognized eolian material and suggested that at least some of the fine-grained material in the upper part of the soil is due to weathering. In some places the fine-grained material is gravel free, whereas in other places it contains gravel. This gravel may have been derived from the underlying material.

The bedrock in Arapaho cirque is Precambrian biotite gneiss with lenses of granodiorite. The biotite gneiss is composed of biotite, quartz, and plagioclase, along with lesser amounts of sillimanite, microcline, garnet, and cordierite (Pearson, 1980). The granodiorite consists chiefly of plagioclase, quartz, biotite, and potassium feldspar (Gable, 1980). We assume that the sand and finer fractions of the glacial and periglacial deposits, as well as the locally derived eolian material, are made up primarily of these minerals. However, if the fine-grained surface layers have been enriched by eolian silt and clay from distant sources, the mineralogy of these fine-grained layers may differ from that of the same size fractions of tills and rock-glacier deposits that are free of eolian sediment.

Stratigraphic Units and Geochronology

The glacial and periglacial deposits in Arapaho cirque (fig. 2) are of Holocene and very latest Pleistocene age (table 1); however, there are differences of opinion regarding the ages of some of the older deposits[3]. Benedict (1967, 1968, 1973, and 1981) and Benedict and Benedict (1984) have done the most detailed mapping and dating of the deposits in Arapaho cirque. Other important contributions have been made by White (1971), Madole (1972), Mahaney (1974), Birkeland and Shroba (1974), Reheis (1975), Davis and Waterman (1979), Davis and others (1979, 1984), and Davis (1982). Meierding and Birkeland (1980) and Burke and Birkeland (1983) have reviewed the previous work in Arapaho cirque and in other cirques in the western United States. The ages of the deposits in these cirques have been estimated from radiocarbon dates and relative-age data such as lichenometry, rock weathering, and soils. All of those who have worked in Arapaho cirque (cited above) agree that the youngest deposit is a till about 100 to 350 years old, based on historical records and lichenometry. It is equivalent to the Gannett Peak deposits identified throughout the Rocky Mountains (Richmond, 1965), therefore the term Gannett Peak is used here rather than Arapaho Peak, a term introduced by Benedict (1973). Downvalley from the Gannett Peak deposits are rock-glacier deposits that all workers agree are of Audubon age. These deposits are about 950 to 2,400 years old, based on radiocarbon dates and lichenometry. Immediately in front of the Audubon deposits is an older rock-glacier deposit designated Triple Lakes by Benedict (1973); Triple Lakes deposits are probably about 3,000 to 5,200 years old, based on radiocarbon dates on younger and older deposits and on lichenometry. The only other deposit in the cirque of interest in this study is till immediately downvalley from the Triple Lakes rock-glacier deposit. The age of the till (the Satanta Peak till deposits of this report) is not agreed on by all workers (Meierding and Birkeland, 1980; Burke and Birkeland, 1983). Benedict (1973) relied mainly on minimum limiting radiocarbon dates (table 1) to suggest that the till is of Triple Lakes age.

There are two reasons for suggesting that the till downvalley of the Triple Lakes rock-glacier deposit is Satanta Peak rather than Triple Lakes as defined by Benedict (1973, 1981). First, five radiocarbon dates on detrital organic matter in sediment from a lake behind the inner moraine (just west of site CO4 in fig. 2) range from 4,730 to 10,410 yr B.P. (see dates of Davis in table 1). Considering that none of the dates are on basal sediment, the date of 10,410 yr B.P. is considered to be a minimum date for the age of the till.

The second reason for suggesting a Satanta Peak age for the till is based on our rock-weathering studies. Of interest here are data for the Triple Lakes rock-glacier deposit and the till immediately downvalley from it (table 2). The rock-weathering data for biotite gneiss are considered to be better indicators of differences in weathering than are those for granodiorite, because granodiorite is not abundant in these deposits and fewer observations were made for granodiorite than for gneiss. Although there are minor differences in the percentage of both weathered and pitted clasts between deposits, pit depths are markedly different between the two deposits. We attribute these differences in weathering to a difference in the ages of the two deposits. We suggest that the till is much older than the rock-glacier deposit, although some of the apparent differences in age could be due in part to the greater length of time between the deposition and stabilization of surface boulders on the rock-glacier deposit than for those on the till.

The best evidence for assessing the age of the till downvalley of the Triple Lakes rock-glacier deposit is the 10,410 yr B.P. radiocarbon date, mentioned above, on lake sediment that postdates the till. Because this date is within the estimated age range of the Satanta Peak till of Benedict (1985) (10,000-12,000 yr), we consider the oldest till that we studied to be Satanta Peak.

Climate

The climate of Arapaho cirque can be approximated by meteorological data from station D-1 (table 3), which is in the alpine tundra on Niwot Ridge, about 4 km to the north (fig. 1). Mean annual precipitation for 1965 through 1970 was 102 cm. Precipitation from October to May is mostly snow. Winter snow is light and dry and can be readily blown from ridges, such as the sites selected for this study. In contrast, late spring snow is heavier and wetter, and

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[3]All of the Quaternary deposits referred to in this report are informal. They are considered allostratigraphic units according to the North American Commission on Stratigraphic Nomenclature (1983).

much of the moisture released by melting infiltrates the soil. The result is that not all of the precipitation is distributed evenly on the landscape. The summer precipitation in the cirque is not well known. A three-year study during all or part of the summers of 1971 through 1973 indicated that precipitation ranged from 16.5 to 31.6 cm (Johnson, 1979). The study area is cold, with a mean annual air temperature of -3.8 ^{o}C and a mean frost-free period of 47 days. The mean annual soil temperature at a depth of 30 cm at station D-1 is -1.1 ^{o}C (Marr and others, 1968; Burns, 1980). Burns (1980) collected soil-temperature data from eight alpine sites on Niwot Ridge east of station D-1; the mean annual soil temperature at these sites ranged from 0.9 to 3.4 ^{o}C. Depending upon local conditions, the soil-temperature regime varies from cryic to

Figure 2. Aerial photograph of Arapaho cirque showing glacial and periglacial deposits and study sites (CO1 to CO8). Deposits at and near study sites, from youngest to oldest, include Gannett Peak till deposits (CO2), Audubon rock-glacier deposits (CO1), Triple Lakes rock-glacier deposit (CO3), and Satanta Peak till deposits (CO4, CO5, CO6, CO7, and CO8). Lake cored by Davis (1982; Davis and others, 1984; Davis, 1987) is just west of site CO4. Source of aerial photograph is unknown.

Table 1. Age control for the glacial and periglacial deposits in Arapaho cirque

[Historical records (H) provide only a minimum age for youngest Gannett Peak till deposits (Benedict, 1968). Lichenometry (L) probably provides only minimum ages, especially for deposits greater than about 2,500 yr old (Benedict, 1985, fig. 43). Radiocarbon ages (R), in years before present, for Audubon rock-glacier deposits are on organic matter from ablation surfaces in ice of rock glacier; those for Satanta Peak till deposits are on organic matter in deposits that are younger than the till deposits, therefore, they provide only minimum ages of the till deposits. Estimated age ranges are from Benedict (1985)]

Deposit		Estimated age range, in yr B.P., for deposits in this report	Age control for deposits		
Benedict (1973)	This report		Dating method	Age (yr B.P.)	References
Arapaho Peak deposits	Gannett Peak till deposits	100-350	H, L	100-250	Benedict (1973)
Audubon deposits	Audubon rock-glacier deposits	950-2,400	L	950-1,850	Do.
			R	955±95	Do.
			R	1,000±90	Do.
Triple Lakes deposits	Triple Lakes rock-glacier deposits	3,000-5,200	L	3,150	Do.
Triple Lakes deposits	Satanta Peak till deposits	10,000-12,000	L	2,850	Do.
			R	2,360±120	Do.
			R	2,560±100	Do.
			R	3,865±100	Do.
			R	4,485±100	Do.
			R	4,730±200	Davis (1982)
			R	5,400±240	Do.
			R	6,430±70	Do.
			R	9,915±380	Davis (1987)
			R	10,410±520	Do.

Table 2. Rock-weathering data

[Rock-weathering data features are defined in Burke and Birkeland (1979); underscored data collected by R.R. Shroba, other data collected by P.W. Birkeland. Rock-weathering sites are shown on figure 2. Values in parentheses refer to number of measurements made. nd, no data]

Site	Deposit	Percent weathered		Percent pitted		Pit depth (mm)			
						Maximum		Mean	
		Biotite gneiss	Grano-diorite	Biotite gneiss	Grano-diorite	Biotite gneiss	Grano-diorite	Biotite gneiss	Grano-diorite
C02	Gannett Peak till deposits	0	0	0	0 0	8	0	7 (2)	0
C01	Audubon rock-glacier deposit	9	27	40	22	30	18	20 (10)	nd
C03	Triple Lakes rock-glacier deposit	29	92	62	96	[1]41	32, 34	24 (26)	nd
C04 C05	Satanta Peak till deposits, inner moraine	39	86	84	85	119	99	62 (26)	nd
C06 C07 C08	Satanta Peak till deposits, outer moraine	nd	nd	nd	nd	142	87, 85	nd	nd

[1]Two pits that may not be entirely due to weathering were 44 and 73 cm deep.

Table 3. Precipitation and temperature data for station D-1, Niwot Ridge, Colorado

[Precipitation data are for 1965 through 1970, and air temperature data are for 1952 through 1970 (Barry, 1973). Soil temperature, taken at 30 cm depth, is mean of weekly maximum and minimum; data are for 1953 through 1958 (Marr and others, 1968) and for 1978, 1979, and part of 1980 (Burns, 1980)]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Mean precipitation (cm)	13.77	9.07	10.54	10.19	6.78	6.99	8.03	5.72	7.16	3.89	11.20	8.76	102.08
Air temperature (°C)													
Maximum } mean -3.8	-10.1	-10.3	-8.2	-3.7	3.1	8.6	12.5	11.3	7.3	1.7	-5.5	-9.1	-.2
Minimum	-16.2	-16.2	-15.2	-11.1	-4.6	.5	4.4	3.4	-.7	-5.4	-11.6	-15.3	-7.3
Soil temperature (°C)	-9.4	-8.9	-8.3	-4.4	-.6	3.3	7.2	7.8	5.0	1.7	-2.8	-7.2	-1.1

pergelic (Soil Survey Staff, 1975). It is likely that the soils in this study have a pergelic soil-temperature regime. The soil-temperature data in table 3 suggest that the soils are frozen for about seven months a year.

Vegetation

Although the vegetation in Arapaho cirque has not been mapped or studied in detail, the plants in the cirque consist primarily of grasses, herbs, sedges, and shrubs (Marr, 1961). Vegetation mapping by Komarkova and Webber (1978) on Niwot Ridge suggests that the alpine plant community type in well-drained areas on the Satanta Peak moraines is alliance Kobresia-Caricion rupestris and association Eritricho-Dryadetum octopetalae. Krummholtz forms of Engelmann spruce and subalpine fir are present on the distal slope of the outer Satanta Peak moraine; however, it is not known if they ever grew at any of the study sites on the Satanta Peak moraines.

The proportion of the non-bouldery ground surface covered by tundra vegetation varies with the age of the deposit. In non-bouldery areas vegetation covers about 25 percent or less of the Gannett Peak deposits, 25 percent of the Audubon deposits, 75 percent of the Triple Lakes deposit, and greater than 75 percent of the Satanta Peak deposits.

Topography

The topographic setting of soil-sampling sites is important in chronosequence studies. The desired strategy in these studies is to select sites where the soil has been forming continuously since the parent material was deposited. Ideally, a site should be relatively unaffected by erosion or by deposition from nearby cirque walls. The sites in this study are on relatively flat (<2 percent slopes), broad ridge crests, or gentle slopes where erosion is thought to be minimal. The sites are located far from cirque walls. Because there commonly is a topographic low between the site and the nearest cirque wall, deposition of cirque-wall debris at these sites is unlikely. Eolian processes are probably the only mechanism by which younger sediment could be transported to the sites following the deposition of the till or rock-glacier debris. Consequently, the properties of each of the soils of this chronosequence should approximate the sum total of pedogenesis since the deposition of the parent material(s) at each of the sites.

SOIL NOMENCLATURE

The soils in this study were described according to the procedures of the Soil Conservation Service (Soil Survey Staff, 1975). Soil-horizon nomenclature is that of the Soil Conservation Service (Soil Survey Staff, 1951; Guthrie and Witty, 1982) combined with the C-horizon nomenclature of Birkeland (1984a). For C horizons, Cox is slightly oxidized material that does not meet the criteria for a cambic (color) B horizon, and Cu is unweathered parent material. The diagnostic horizons are those defined by the Soil Survey Staff (1975) for classification purposes.

The soil names in this report are informal. They are formed by adding the prefix "post" to the name for the soil parent material. For example, the soil formed from till of the Gannett Peak advance is termed the post-Gannett Peak soil.

SITE SELECTION AND SAMPLING PROCEDURES

Sites were selected in order to maximize soil development. Because so little of the Gannett Peak moraine has any alpine plants, the soil was collected on the outermost moraine where a small cluster of plants was growing. Rock-glacier deposits are difficult for soil sampling because stable sites on ridges are not common, therefore, there were few suitable sites on the Audubon and Triple Lakes rock-glacier deposits. In contrast, there are many stable, well-vegetated sites on the crests of Satanta Peak moraines. We described and sampled several soil profiles from the inner and outer Satanta Peak moraines in order to determine (1) if there were any differences between the soils on the same moraine, (2) if there were any pedological differences between moraines that correspond with differences in relative age, and (3) the reproducibility of the field and laboratory data.

Channel samples were collected for each soil horizon. The samples were screened in the field; material larger than 3 mm in diameter was discarded. Prior to laboratory analyses, the samples were passed through a 2-mm screen. All of the analyses, as well as air-dry color, were performed on material less than 2 mm in size.

DEFINITIONS OF THE CHEMICAL EXTRACTS

Chemical extracts of iron, aluminum, and phosphorus commonly exhibit systematic pedological trends with time (see Birkeland, 1984a, for examples and references). The dithionite-citrate method determines the amount of free iron and aluminum n oxides, hydrous oxides, and organic substances. Most of these forms of iron and aluminum do not occur in the parent material. Five forms of phosphorus (P) were measured; they include: calcium-bound P (Pca) in the original minerals, occluded P (Poc) in coatings or concretions composed of oxides and hydrous oxides of iron and aluminum, non-occluded P (Pnoc) on the surfaces of the above oxides and hydrous oxides, organic-bound P (Po), and total P (Pt), which is the total of the above forms.

TRENDS IN THE FIELD AND LABORATORY DATA FOR THE SOIL CHRONOSEQUENCE

Systematic trends in field and laboratory data have been observed for most soil chronosequences (Birkeland, 1984a). On the basis of data for similar soils in areas of similar climate, we hypothesized that the soils in the study area would have the following trends with time. A horizons would (1) increase in thickness, (2) become darker (decrease in color value), and (3) differ in percentages of organic carbon (C) and nitrogen (N). B horizons would (1) increase in thickness and clay content, (2) develop redder hues and higher chromas, and (3) possibly have clay films and silt caps (coatings composed of silt and clay) on clasts (Burns, 1980; Birkeland, 1984a, appendix 1). Cox horizons would (1) increase in thickness and (2) develop redder hues and higher chromas. The pH values of A and B horizons should show an overall decrease with time, cation exchange capacity (CEC) should increase as the amounts of organic matter and clay content increase, and dithionite-extractable iron (Fed) and aluminum (Ald) should increase. Phosphorus trends are complex because they depend on the degree of leaching (Walker and Syers, 1976). In general, with sufficient leaching, acid-extractable calcium-bound P should decrease; occluded, non-occluded, and organic-bound P should increase; and total P should decrease.

The morphology and the physical, chemical, and mineralogical properties of the soils in Arapaho cirque exhibit numerous significant trends with time (supp. tables 1-4, respectively).

POST-GANNETT PEAK SOIL

The post-Gannett Peak soil is an A/Cox profile that is only 3 cm thick. This soil has minimal development and lacks diagnostic horizons. It is classified as a Pergelic Cryorthent (Soil Survey Staff, 1975). The A horizon is 0.5 cm thick and patchy; the Cox horizon is thin and very weakly oxidized. The percentages of total sand, silt, and clay suggest a change in parent material between the Cox and Cu horizons, even though the percentages for the various sand-size fractions do not seem to support this interpretation. Chemical data indicate considerable pedogenesis in the A and Cox horizons relative to the Cu horizon[4]. Specifically, pH has decreased, exchange acidity has increased, and there are increases in C, N, Fed, Ald, and Po that are more likely to be pedogenic than due to variations in the parent material. The ranking of the exchangeable cations according to their relative abundances is Ca $\gg$ K $>$ Na, and no Mg. The ranking of the clay-mineral peaks according to their relative heights is kaolinite $\simeq$ mica $>$ chlorite $\simeq$ smectite $>$ vermiculite. Kaolinite and mica peaks are slightly higher in the A horizon than in the Cu horizon.

POST-AUDUBON SOIL

The post-Audubon soil is an A/AC/Cox profile that is different from the post-Gannett Peak soil in some morphological and chemical characteristics. The A and AC horizons have a combined thickness of 27 cm. Although they are relatively dark, they do not meet the color requirements of the mollic or umbric epipedon. The Cox horizon is not red enough to qualify as a cambic horizon. This soil, therefore, is classified as a Pergelic Cryorthent even though it is better developed than the post-Gannett Peak soil. Sand-fraction data suggest a change in the parent material at a depth of 27 cm, but because the total amounts of sand, silt, and clay are fairly uniform with depth, and a change in parent material was not identified in the field, the parent material is considered to be uniform throughout the profile. Chemical trends are somewhat similar to those for the post-Gannett Peak soil; however, some of the chemical data for the post-Audubon soil have higher values than those of the post-Gannett Peak soil or indicate a greater depth of chemical alteration. The ranking of the exchangeable cations according to their relative abundances are the same as for the post-Gannett Peak soil, but the amounts are higher. The ranking of the clay-mineral peaks according to their relative heights is fairly similar in each horizon, with smectite $\geq$ kaolinite $>$ mica $>$ chlorite $\geq$ vermiculite(?). Vermiculite(?) occurs in only the A horizon.

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[4]The total chemical composition of the soils in Arapaho cirque are presented in supplementary tables 5 and 6. Although these data are not discussed in the text, they are included in this report because they serve as a chemical data base for the soils, and they aid in the interpretation of the extractive chemical properties and clay mineralogy of the soils.

POST-TRIPLE LAKES SOIL

The post-Triple Lakes soil has an A/Bw/Cox profile. It is different from the post-Audubon soil because it has a B horizon. The dark color of the A horizon, the content of organic carbon, and a base saturation value of 50 percent place it on the border between a mollic and umbric epipedon. The B horizon is a cambic[5] (color) B with a 10YR hue and chromas of 3 and 4. This soil is either a Pergelic Cryumbrept or a Pergelic Cryoboroll. Parent material layering may account for the slight increase in silt and clay in the A horizon, or some of these fines could be due to the addition of airborne dust. Some of the chemical properties, such as pH and Fed, are similar to those for the post-Audubon soil but the other properties are markedly different. For example, exchange acidity, C, N, Ald, and Po are all much higher for the post-Triple Lakes soil than for the post-Audubon soil. The data for the other P fractions are difficult to interpret, but if the values for the post-Gannett Peak soil are considered to be an approximation of parent material values, then the relatively low values for Pca, except for the B horizon, suggest loss of P owing to the weathering of apatite. The high value of Pca in the B horizon cannot be explained. This is the youngest soil to have Mg on the exchange complex, and it is present only in the A horizon where the relative abundance ranking of the exchangeable cations is Ca $\gg$ K $>$ Mg $>$ Na. Clay mineral peak heights suggest the following ranking: smectite $\geq$ kaolinite $>$ mica.

POST-SATANTA PEAK SOILS

The post-Satanta Peak soils are characterized by an A/Bw (or Bt)/Cox profile, and are the best developed soils of the chronosequence. Soils at sites CO4 and CO6 have mollic epipedons, those at CO5 and CO7 have umbric epipedons, and the soil at CO8 has an ochric epipedon. B horizons have 10YR and 7.5YR hues and chromas of 4 and 5. Three of the five soils have Bt horizons that have a sufficient clay increase to qualify as argillic horizons (Soil Survey Staff, 1975). Typically, the argillic horizon is defined on the basis of the clay content of the B horizon compared to that of the A horizon. In these soils, however, the higher silt and clay content of the A horizon relative to that of the underlying till suggests the presence of some airborne dust in the A horizon. Much of this dust may remain in the A horizon, although some of it may be translocated into the B horizon, producing more of a textural contrast between the B and C horizons than between the A and B horizons. In such cases, we use the clay content of the B horizon versus that of the C horizon to determine whether or not a B horizon is argillic[6].

The post-Satanta Peak soils belong to several different taxonomic units. The soil at CO8 is a Pergelic Cryochrept, the soil at CO7 is a Pergelic Cryumbrept, and those with argillic horizons are either Argic Pergelic Cryoboroll (CO4) or Pergelic Cryoboralf (CO5 and CO6). The last term is not in Soil Taxonomy (Soil Survey Staff, 1975), but it is used here to refer to cold soils (mean annual temperatures less than 0 °C) with argillic horizons. Parent material layering is common in these soils; it is identified by the variation in gravel content with depth and by the difference in texture of the near-surface horizons. Except for pH and Pt, most values for chemical properties are commonly as much as 2 times greater than those for the post-Triple Lakes soil. In contrast, Pca values are much less for the post-Satanta Peak soils than they are for the post-Triple Lakes soil, and may indicate more intense leaching and (or) prolonged leaching of the post-Satanta Peak soils. A large proportion of exchangeable Mg exists in these soils, especially in the A horizons, where the ranking of exchangeable cations is Ca $>$ Mg $>$ K $>$ Na. The general trend of the clay mineral peak heights for the five soils is kaolinite $\simeq$ smectite $>$ mica $\geq$ chlorite $\geq$ interstratified mica-chlorite. Depth trends are difficult to interpret, but smectite is low at depth and increases in either the A or B horizon, mica increases toward the surface, and kaolinite decreases toward the surface. These trends could be due primarily to chemical weathering and (or) the addition of airborne dust to the near-surface horizons.

SUMMARY OF SOIL-PROFILE CHARACTERISTICS

Several trends with time are readily apparent. One is the genetic sequence of soil taxonomic units: Pergelic Cryorthent (as much as about 2,000 yr) to Pergelic Cryumbrept (about 4,000 yr) to Pergelic Cryoboralf (about 10,000-12,000 yr). Color B horizons with a 10YR hue, that we designate as cambic horizons, form in about 2,000 to 4,000 years. Bt horizons with a 10YR or a 7.5YR hue, that we designate as argillic horizons, form in about 5,000 to 12,000 years. Most chemical properties show progressive change with time. By about 1,000 to 2,000 years, pH has reached minimum values common to all of the older soils. In contrast, all other chemical properties continue to change over the duration of the chronosequence. It is not known if the oldest soils are in a steady-state condition because data for older soils would be needed to make this judgment. In general,

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[5]According to the Soil Survey Staff (1975), the B horizon meets the color requirement, but is too coarse grained to meet the textural requirement for a cambic horizon. We recommend waiving the textural requirement, because it is too arbitrary for pedologic studies; therefore, the B horizon is here considered to be a cambic horizon. For comparison, the parent material color is considered to be the same as that of the Cu horizon of the post-Gannett Peak soil (supp. table 1).

[6]The Bt horizons of the post-Satanta Peak soils are considered to be argillic horizons, on the basis of clay content, even though they lacked clay films when examined in the field. Soil thin sections are needed in order to definitely determine the presence or absence of translocated clay, which is diagnostic of argillic horizons.

CEC increases with time. It tends to increase with both organic matter and clay content, although it is also dependent in part on the type of clay minerals present. The exchangeable cations display the following trends: Na and K are present in low amounts and show slight increases with time; Ca is the dominant cation for soils of all ages, and it increases with time; and Mg occurs first in the post-Triple Lakes soil where it is restricted to the A horizon, and is second to Ca in abundance. These trends could be due to soil-forming processes and (or) the addition of airborne dust with exchangeable cations dominated by Ca and Mg. The amounts of C and N in the A horizons increase systematically with time; the C/N ratio of the A horizons, however, shows little change with time.

Eolian materials are important to some of the properties of some of the soils in Arapaho cirque. Material collected from melting snow and ice at the end of the ablation season is considered to be representative of the local eolian materials. One sample from Arapaho Glacier has a sand/silt/clay percentage ratio of 38/42/20 (Burns, 1980). Other data also show that the eolian materials of the region are fine grained (Thorn and Darmody, 1980, 1985; Burns, 1980). In alpine areas, eolian material could theoretically either (1) form a discrete surface layer, (2) be physically mixed with till or other coarse-grained deposits, or (3) some of it, mainly the silt and clay fractions, be translocated to depth in the soil. Translocation of eolian material may have produced some of the silt caps on clasts in the post-Audubon and older soils, and may account for much of the clay accumulation in the Bt horizons of some of the post-Satanta Peak soils[7].

Trends in clay mineralogy are difficult to interpret because the primary clay minerals can come from different sources: the glacial and periglacial parent materials or eolian materials. Once deposited, the clays may alter to more stable minerals, and some or most of them may be translocated downward in the profile. The clay mineralogy of the Cu horizon of the post-Gannett Peak soil is characterized by kaolinite $\sim$ mica $>$ smectite $>$ vermiculite and should approximate that of the parent material at depth in all of the profiles. The clay mineralogy of the material collected on Arapaho Glacier is characterized by mica $>$chlorite $>$ kaolinite$\sim$ smectite and 1-1.4 nm mixed-layer clay (Burns, 1980), and may be similar to that of eolian material added to the soils of this study. Trends in clay mineralogy over the past 12,000 years seem to be the depletion and (or) dilution of kaolinite, smectite, and mica, and the formation and (or) addition of 1-1.4 nm mixed-layer clay minerals. We cannot discriminate between trends due chiefly to pedogenic processes and those due chiefly to eolian processes.

[7] Not all silt caps are pedologic features, because some of them occur in deposits unaffected by pedogenesis (P.W. Birkeland, unpub. data, 1984). These non-pedogenic silt caps are considered to be a parent material property.

COMPARISON WITH PREVIOUS WORK

The data presented in this report compare well with those for other soil chronosequence studies in the Colorado Front Range and the rest of the Rocky Mountain region.

Benedict (1973) did the initial fieldwork on the soils in Arapaho cirque. The soil morphological trends he described are very similar to those in this report. He did not describe a soil on the Triple Lakes rock-glacier deposit (soil CO3), and he indicated that there was considerable overlap in the properties of the soils formed from the type Triple Lakes till (the post-Satanta Peak soils of this study) and the type Satanta Peak till. Data for the soil formed in the type Satanta Peak till at Caribou Lake (fig. 1) are presented in Birkeland and Shroba (1974) and Benedict (1985). The overlap in morphological properties of the above soils can be attributed to soil-forming factors other than time, or the type Triple Lakes till (the Satanta Peak till deposits of this study) and the type Satanta Peak till could be the same age. Mahaney (1974) did the first detailed work on the soils in this area of the Colorado Front Range that included laboratory analyses. In general, we agree with most of Mahaney's morphological and analytical data.

Mahaney's work differs from ours in that he (1) described a much thicker Cox horizon for the post-Gannett Peak soil than we did, (2) reported only 10YR-hue colors for both the post-Gannett Peak and post-Audubon soils, and (3) identified an iron-enriched Bs horizon (his Bir horizon) in one of his post-Triple Lakes soils. In addition, he used 4 micrometers as the upper size limit for the total clay fraction, whereas 2 micrometers is the accepted size limit between silt and clay.

Our main differences with the work of Dixon (1983) are that he recognized a B horizon in the post-Audubon soil, and the clay percentages that he obtained for most of his soils are higher than ours.

Albino (1984) reported trends in soil development with time that are similar to those of this study, although she recognized B horizons in her post-Gannett Peak soil and in one of her post-Audubon soils, and she reported Fed values that are higher than those we report for our soils.

Shroba (1977; Shroba and Birkeland, 1983) studied alpine soils equivalent in age to those in Arapaho cirque over a large region of the Rocky Mountains and reported findings that are similar to ours. Broad similarities are also seen between alpine soils in Arapaho cirque and soils of similar ages in the Wind River Mountains, Wyoming (Miller and Birkeland, 1974). We believe that the similarity of soil properties reported by different workers throughout the Rocky Mountains lends credence to the use of soils as a criterion for broad, regional correlations of Quaternary deposits.

Trends in the relative abundance of clay minerals with time reported in other studies of Holocene soils in the region differ somewhat from those of this study. Mahaney (1974) reported that illite decreased and chlorite, montmorillonite, and mixed-layer illite-montmorillonite increased with time in soils in Arapaho cirque. Dixon's (1983, 1986) work in Arapaho cirque indicated depletion of kaolinite and the alteration of biotite to hydrobiotite, vermiculite, and smectite. In a cirque 6 km south of Arapaho cirque, Albino (1984) recognized the depletion of mica, chlorite, and randomly interstratified mica/smectite, and the formation of ordered mica/smectite and intergrade chlorite. In the Colorado Rocky Mountains, Shroba (1977; Shroba and Birkeland, 1983) described a decrease in mica and an increase in mixed-layer clays (1-1.8 nm) with time in alpine areas that may have never been forested.

TRENDS IN SOIL DEVELOPMENT INDICES WITH TIME

Definitions

Soil field descriptions are quite complicated and involve many qualitative observations and some quantitative measurements. Several indices have been devised to integrate the descriptive data for either a horizon or an entire profile into a single numerical value that serves as a ranking of the degree of development of the horizon or profile. Two of the better known indices have been developed by Bilzi and Ciolkosz (1977) and Harden (1982a; Harden and Taylor, 1983). Both indices are somewhat similar in that the properties of each horizon are compared to those of either the C horizon (Bilzi and Ciolkosz, 1977) or the parent material (Harden, 1982a). A numerical value is assigned based on the difference between two horizons or a horizon and the parent material. For both methods, a total value can be calculated for each horizon; the larger the value, the more the horizon differs in most pedological properties from either the C horizon or the parent material. One problem with each of these methods is that soils commonly develop to different depths. The difference in depths alone can have a major influence on index values, because horizon index values are multiplied by horizon thickness.

For this study we have modified each of the methods so that they will yield a value more closely related to profile development to a uniform depth (see discussion in Birkeland, 1984a, and in Harden and Taylor, 1983). In order to take into account the fact that soils commonly are described to different depths, we increased the thickness of the lowest horizon so that each profile had the same thickness as the thickest soil of the chronosequence, which in this study was 85 cm. Although this approach created some problems (Birkeland, 1984a), it permitted comparison of the soils to a common depth. Higher index values in these systems usually correspond to greater soil development.

The systematic reddening of soil color with time in well-drained soils has also been the basis for other development indices. The Munsell color notations can be converted to a single index value; three such indices are used here to assess soil development. The first is the Buntley-Westin (B-W) color index (Buntley and Westin, 1965), in which hue is assigned a numerical value (7.5YR=4, 10YR=3, 2.5Y=2, 5Y=1) that is multiplied by the chroma. The second is the Hurst (H) color index (Hurst, 1977), in which hue is assigned a numerical value (5YR=15, 7.5YR=17.5, 10YR=20, etc.) that is multiplied by the fraction formed by the value and chroma (value/chroma). The third is rubification, one of several properties of the soil development index of Harden (1982a), in which the color of each horizon is compared with that of the parent material. In this system, each shift toward a redder hue and each shift toward higher chromas is assigned a value of 10 points. For all three color indices, we multiplied the numerical value for each horizon by horizon thickness, once the thickness of the lowest horizon was adjusted so that the thickness of all profiles was the same (85 cm). We then summed the horizon values to yield a total value for the soil profile. Both the B-W color index and rubification increased with the redder hues and higher chromas that accompany greater degree of pedogenesis, whereas the H color index decreased.

One problem common to all of these color indices is that the effect of eolian parent materials is not known. In this report, we considered the colors of the eolian parent materials to be similar to those of the glacial parent materials, although these colors may not be representative of all of the soil parent materials. This is especially true if some of the eolian parent materials were derived from previously weathered deposits.

Results

The point values for each of the index systems change in a systematic manner with time (table 4). Both of the profile-development indices increase with time (fig. 3). Values for both indices define linear functions and have similar correlation coefficients (table 5). All color indices change with time (fig. 4). Both rubification and B-W values define linear functions. Rubification has a higher correlation coefficient than the B-W index. In contrast, values for the H index define a power function with a high, negative correlation coefficient. Comparison of the standard deviations of the various indices for the post-Satanta Peak soils, expressed as a percentage of the mean (table 6), indicates that the profile indices have less variation than the color indices, and that the rubification and H indices have less variation than the B-W index.

We calculated the above indices to assess their usefulness for the correlation of surficial deposits in alpine environments. The results presented in this report are encouraging, as are those for the Wind River Mountains, Wyoming (fig. 1-10 in Birkeland, 1984a) and those for part of the Southern Alps, New Zealand (Birkeland, 1984b). More work on soil indices in different areas is needed in order to further test their usefulness.

CONCLUSIONS

One of the goals of soil chronosequence studies is to evaluate the usefulness of various soil properties for estimating the ages of surficial deposits. The discussion in this report pertains to cirque deposits above treeline in the Colorado Front Range. Detailed field descriptions are essential in soil chronosequence studies because field-description data can be used to calculate index values that may be useful age indicators.

For greater accuracy, color data collected in the field should be compared with data for the air-dried seived samples, because the latter give the most consistent results. Laboratory data vary in their usefulness in soil chronosequence studies. In this study, the most useful laboratory data for differentiating deposits of different ages were particle size, Fed, Ald, Pca, C, and N.

Table 4. Values for soil-profile and color indices of the soils

[All values are for 85-cm-thick soil profiles. Soil-profile sites are shown on figure 2. Buntley-Westin and Hurst color indices refer to dry colors. nd, not determined]

Site	Soil	Profile indices				Color indices					
		Bilzi-Ciolkosz (X100)		Harden		Buntley-Westin (X100)		Hurst (X1000)		Rubification (X1000)	
C02	Post-Gannett Peak	0.18		0.008		0.15		12.59		0.002	
C01	Post-Audubon	4.23		.194		4.65		4.83		2.80	
C03	Post-Triple Lakes	6.32		.213		5.49		4.09		6.71	
C04	Post-Satanta Peak	8.41	X̄=9.14	.288	X̄=0.362	10.32	X̄=9.79	2.21	X̄=2.53	8.79	X̄=8.58
C05		8.91		.367		17.60		2.07		9.22	
C06		10.54		.388		9.82		2.06		10.60	
C07		10.00		.403		6.75		2.66		7.90	
C08		7.85		nd[1]		4.44		3.64		6.40	

[1] No pH data. Because pH is important to the calculation of Harden's profile index, the profile index was not determined for this soil.

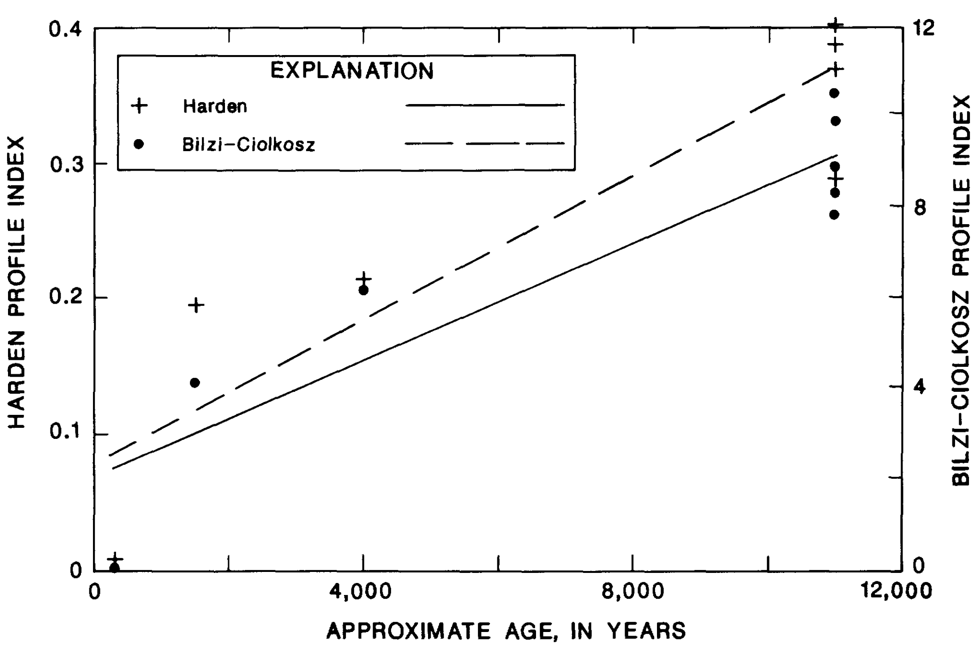

Figure 3. Plot of profile-development indices versus approximate age of soil parent materials. Trend lines based on regression equations in table 5; data from supplementary table 1. Ages of soil parent materials used to plot data are as follows: 300 yr for Gannett Peak deposits; 1,500 yr for Audubon deposits; 4,000 yr for the Triple Lakes deposit; and 11,000 yr for Satanta Peak deposits.

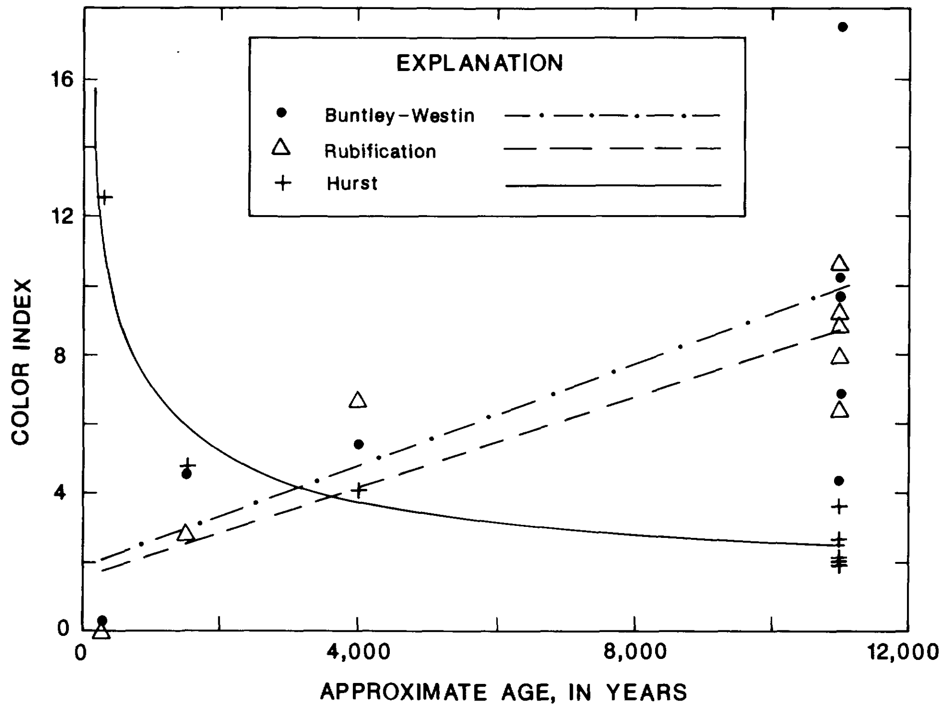

Figure 4. Plot of color indices versus approximate age of soil parent materials. Trend lines based on regression equations in table 5; data from supplementary table 1. For ages of soil parent materials, see figure 3.

Table 5. Regression-equation data for the soil-profile and color indices

[Regression models used: 1, linear; p, power. X, age of soil parent material in years]

Property (Y)	Model	Regression equation	Correlation coefficient	Significance level
Harden index	1	Y = 0.08 + 0.000026 X	0.91	0.01
Bilzi-Ciolkosz index	1	Y = 2.08 + 0.00065 X	.92	.01
Buntley-Westin index	1	Y = 1.88 + 0.00073 X	.67	.10
Hurst index	p	log Y = 2.14 - 0.432 log X	-.95	.001
rubification	1	Y = 1.62 + 0.00065 X	.88	.05

Table 6. Selected statistical measures for the soil-profile and color indices for the post-Satanta Peak soils

[Individual index values are listed in table 4]

Statistical measure	Profile indices		Color indices		
	Bilzi-Ciolkosz (X100)	Harden	Buntley-Westin (X100)	Hurst (X1000)	Rubification (X1000)
Mean	9.14	0.362	9.79	2.53	8.58
Standard deviation	1.11	.051	4.98	.67	1.56
Standard deviation as a percentage of the mean	.12	.141	.51	.26	.18

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SUPPLEMENTARY TABLES

Supplementary table 1. Field descriptions

[nd, not determined; no, not observed. Analysts: P. Birkeland, R. Burke, and J. Harden]

Site[1]	Horizon	Basal depth (cm)	Lower boundary[2]	Color[3] Moist	Color[3] Dry	Percentage[4] of >2-mm	Texture[5]	Structure[6]	Consistence[7] Moist	Consistence[7] Wet	Roots[8]	Pores[9]	Clay films
						Gannet Peak till deposits, 0.1-0.35 ka							
C02	A	0.5	a,s	10YR3/2	10YR4/2	75	SL	sg	lo	ss,po	1 med+ fi	no	no
	Cox	3	c,w	nd	2.5Y6/2	75	SL	sg	lo	ss,po	1 fi	no	no
	Cu	18+	no	7.5Y4/1	7.5Y5.5/1	75	SL	sg	lo	ss,po	no	no	no
						Audubon rock-glacier deposits, 0.95-2.4 ka							
C01	A	7	c,w	10YR2/2	10YR2/2.5	75	coSL	sg	lo	so,po	3 fi + med	no	no
	AC	27	c,w	10YR4/3	10YR6/3	75	coSL	sg	lo	so,po	3 fi + med	no	no
	Cox	45	d,nd	2.5Y4/3	2.5Y6/2	75	coSL	sg	lo	so,po	1 fi	no	no
	Cox	75+	no	2.5Y4/3	2.5Y6/2	75	coSL	sg	lo	so,po	1 fi	no	no
						Triple Lakes rock-glacier deposit, 3-5.2 ka							
C03	A	12	c,w	10YR2/2	10YR3.5/2	nd	coSL	2 med sbk	lo	so,po	3 med, 2 fi	1 med tub	no
	2A	24	c,w	10YR2/3	10YR4/3	75	coSL	1 med sbk	fr	so,po	3 med, 2 fi	1 med tub	no
	2Bw	49	c,w	10YR4/4	10YR5.5/3	75	LcoS	sg	lo	so,po	no	no	no
	2Cox	58+	no	2.5Y4/1	2.5Y6/2	75	coSL	sg	lo	so,po	no	no	no
						Satanta Peak till deposits, inner moraine, 10-12 ka							
C04	A	14	c,w	10YR3/2	10YR4/2	10	fiSL	m, 1 med sbk	fr	so,po	3 fi, 2 med, 1 co	1 med tub	no
	2Bt	38	g,w	7.5YR3/4-4/5	7.5YR4/4-5/4	75	SL	2 med sbk	fr	so,po	2 med	1 fi tub	no
	2BC	62+	no	10YR3.5/4	10YR5/4	75	coSL	sg	lo	so,po	no	--	no
C05	A	13	c,w	7.5YR2/2	7.5YR3/2	25	coSL	m, 1 med sbk	fr	so,po	3 fi, 2 med	1 med tub	no
	2Bt	31	c,w	10YR3/5	10YR4/5	75	SL	1 med sbk	fr	so,po	3 med	1 med tub	no
	2Cox	85+	no	10YR3/3	10YR4/3	75	coSL	sg	lo	so,po	2 med, 2 fi	--	no
						Satanta Peak till deposits, outer moraine, 10-12 ka							
C06	A	15	c,w	7.5YR2/2	7.5YR2/2	10	L	m, 2 med sbk	fr	so,po	3 fi + med	1 med tub	no
	2Bt	38	c,w	7.5YR3/4	7.5YR4.5/4	25	coSL	2 med sbk	fr	ss,po	no	1 fi tub	no
	2Cox	80+	no	7.5YR3/4	10YR5/3.5	75	coLS	sg	fr	so,po	no	2 fi tub	no
C07	A	11	c,w	10YR2/2	10YR2/2	10	fiSL	m, 1 med sbk	fr	so,po	2 med, 1 fi	1 med tub	no
	2AB	16	c,w	10YR2/3	10YR3/3	25	SL	1 med sbk	fr	so,po	2 med, 1 fi	1 med tub	no
	2Bw	41	c,w	10YR3.5/4	10YR5.5/4	25	SL	2 med sbk	fr	ss,po	2 med, 2 fi	1 fi tub	no
	2Cox	80+	no	2.5Y3/3	2.5Y5/3	50	SL	1 med sbk	fr	ss,po	1 fi	2 fi tub	no
C08	A	9	c,w	7.5YR2/2	7.5YR3/2	10	L	2 med sbk	fr	so,po	2 med, 2 fi	1 med tub	no
	2Bw	25	g,w	10YR3/4	10YR5/4	25	SL	2 med sbk	fr	so,po	2 med, 2 fi	1 fi tub	no
	2Cox	85+	no	5Y4.5/3	5Y6/3	75	coSL	1 fi abk	lo	so,po	1 fi	1 fi tub	no

[1]Soil-profile sites are shown on figure 2.
[2]Lower horizon boundary is given in two parts: (1) distinctness a, abrupt; c, clear; g, gradual, d, diffuse; (2) topography: s, smooth; w, wavy.
[3]Color is the Munsell color of the fraction less than 2 mm in size.
[4]Percentage of material larger than 2 mm in size is based on visual estimates.
[5]Texture of the material less than 2 mm in size is based on sieve and pipette analyses: co, coarse; fi, fine; L, loam; LS, loamy sand; SL, sandy loam; S, sand.
[6]Except for massive (m) and single grain (sg), structure is given in three parts: (1) grade: 1, weak; 2, moderate; (2) size: fi, fine; med, medium; (3) type: sbk, subangular blocky; abk, angular blocky.
[7]Moist consistence is either loose (lo) or friable (fr). Wet consistence is given in two parts: (1) stickiness: so, non-sticky; ss, slightly sticky; (2) plasticity: po, non-plastic.
[8]Data for roots are given in two parts: (1) abundance: 1, few; 2, common; 3, many; (2) size: fi, fine; med, medium; co, coarse.
[9]Data for pores are given in three parts: (1) abundance: 1, few; 2, common; (2) size: fi, fine; med, medium; (3) shape: tub, tubular.

Supplementary table 2. Physical properties

[na, sample not analyzed; nd, not determined. Analysts: A. Busacca, P. Janitsky, R. Meixner under M. Singer, University of California, Davis, and R. Kihl, University of Colorado]

Site[1]	Horizon	Basal depth (cm)	Percentage of <2-mm fraction								
			Sand[2]					Silt[3]	Clay[4]		
			Total	vco	co	med	f+vf	Total	Total	co	f
			Gannett Peak till deposits, 0.1-0.35 ka								
C02	A	0.5	82.2	19.1	14.6	12.0	36.5	10.9	6.9	3.7	3.2
	Cox	3	85.6	37.7	20.3	9.3	18.3	8.3	6.1	3.5	2.6
	Cu	18+	69.2	19.6	14.1	9.1	26.8	20.0	10.4	4.3	6.1
			Audubon rock-glacier deposits, 0.95-2.4 ka								
C01	A	7	80.7	18.5	14.2	11.1	36.9	11.9	7.4	3.0	4.4
	AC	27	82.6	21.1	18.1	11.8	31.6	10.5	6.9	3.4	3.5
	Cox	75	85.0	32.1	18.0	10.2	24.7	7.8	7.2	4.2	3.0
			Triple Lakes rock-glacier deposit, 3-5.2 ka								
C03	A	12	74.4	14.4	14.8	10.4	34.8	15.0	10.6	3.9	6.7
	2A	24	74.9	14.3	16.4	11.3	32.8	15.0	10.1	4.2	5.9
	2Bw	49	80.8	20.5	19.7	12.0	28.5	11.3	7.9	4.5	3.4
	2Cox	58+	71.7	13.9	15.8	10.8	31.2	20.4	7.9	4.7	3.2
			Satanta Peak till deposits, inner moraine, 10-12 ka								
C04	A	14	62.2	5.7	6.6	6.0	43.9	28.6	9.2	1.6	7.6
	2Bt	38	60.1	13.5	12.8	8.4	25.4	25.8	14.1	4.1	10.0
	2BC	62+	86.7	22.3	16.9	10.0	27.5	6.2	7.1	3.0	4.1
C05	A	13	61.7	21.5	13.7	7.2	19.3	28.8	9.5	1.5	8.0
	2Bt	31	63.6	17.3	12.6	8.3	25.4	26.3	10.1	1.3	8.8
	2Cox	85+	75.1	20.9	15.5	10.1	28.6	18.0	6.9	2.3	4.6
			Satanta Peak till deposits, outer moraine, 10-12 ka								
C06	A	15	53.1	17.9	12.6	6.7	16.2	33.0	13.9	7.0	6.9
	2Bt	38	66.8	17.5	14.5	9.5	25.3	24.1	9.1	2.2	6.9
	2Cox	80+	86.3	21.6	21.3	15.5	27.9	10.7	3.0	1.1	1.9
C07	A	11	71.5	14.7	14.4	8.2	34.2	21.7	6.8	2.0	4.8
	2AB	16	na	na	na	na	na	na	na	na	na
	2Bw	41	64.8	13.6	12.6	9.2	29.4	25.9	9.3	3.1	6.2
	2Cox	80+	67.7	15.1	12.6	9.5	30.5	25.2	7.1	3.0	4.1
C08[5]	A	9	69.2	20.6	18.9	8.3	nd	22.5	8.4	0.5	7.9
	2Bw	25	74.1	20.0	16.6	10.7	26.8	20.6	5.3	2.6	2.7
	2Cox	85+	74.3	16.5	15.4	10.0	nd	18.4	7.4	4.0	3.4

[1]Soil-profile sites are shown on figure 2.
[2]Size ranges of the sand fraction are: total (2-0.05 mm); vco, very coarse (2-1 mm); co, coarse (1-0.5 mm); med, medium (0.5-0.25 mm); f+vf, fine and very fine (0.25-0.05 mm).
[3]Silt is 0.05 to 0.002 mm (50 to 2 μm) in size.
[4]Size ranges of the clay fraction are: total (<2 μm); co, coarse (2-1 μm); f, fine (<1 μm).
[5]Analyzed by R. Kihl, University of Colorado.

Supplementary table 3. Extractive chemical analyses[1]

[na, sample not analyzed; nd, not determined. Analysts: A. Bussacca, P. Janitsky, R. Meixner, under M. Singer, University of California, Davis]

Site[2]	Horizon	Basal depth (cm)	Percentage of <2-mm		meq/100g soil						Percentage of <2-mm		pH		Phosphorus[4]					
			Total N	Organic C	Exchangeable cations				H	CEC	Fe_d	Al_d	1:1H2O	1:1KCl	Pt	Pnoc	Poc	Pca	Po	Pt
					Na	K	Ca	Mg												
										Gannet Peak till deposits, 0.1-0.35 ka										
C02	A	0.5	0.068	1.5	0.010	0.22	2.93	0.00	3.11	4.49	0.60	0.068	5.4	4.10	208.0	20.0	72.0	100.0	17.0	209.0
	Cox	3	0.011	0.12	0.020	0.09	3.53	0.00	0.94	3.08	0.53	0.051	5.4	4.37	nd	33.0	92.0	91.0	3.0	219.0
	Cu	18+	0.010	0.11	0.020	0.36	3.53	0.00	0.82	3.33	0.44	0.043	6.3	4.86	181.0	8.0	99.0	123.0	0.0	230.0
										Audubon rock-glacier deposits, 0.95-2.4 ka										
C01	A	7	0.154	2.07	0.030	0.28	5.15	0.00	5.61	8.66	0.70	0.125	5.5	4.20	402.0	49.0	106.0	131.0	120.0	407.0
	AC	27	0.039	0.44	0.020	0.13	3.23	0.00	6.41	4.49	0.64	0.085	5.6	4.20	305.0	66.0	143.0	103.0	0.0	312.0
	Cox[3]	75+	0.023	0.22	0.001	0.13	4.34	0.00	1.91	4.41	0.52	0.055	5.6	4.20	239.0	30.0	132.0	98.0	0.0	260.0
										Triple Lakes rock-glacier deposit, 3-5.2 ka										
C03	A	12	0.398	5.82	0.020	0.73	11.72	0.50	10.26	22.56	0.55	0.196	5.8	4.96	940.0	91.0	161.0	84.0	618.0	954.0
	2A	24	0.185	2.27	0.020	0.27	4.34	0.61	8.36	11.99	0.77	0.211	5.5	4.35	680.0	60.0	67.0	78.0	482.0	687.0
	2Bw	49	0.058	0.48	0.020	0.08	2.32	0.00	4.79	5.08	0.55	0.159	5.4	4.16	420.0	44.0	55.0	130.0	175.0	404.0
	2Cox	58+	0.021	0.20	0.040	0.11	3.74	0.00	2.45	4.58	0.45	0.113	5.7	4.12	149.0	15.0	28.0	22.0	85.0	150.0
										Satanta Peak till deposits, inner moraine, 10-12 ka										
C04	A	14	0.462	7.30	0.040	0.50	9.39	6.47	13.27	29.05	0.63	0.225	5.5	4.77	732.0	65.0	56.0	46.0	579.0	746.0
	2Bt	38	0.190	2.33	0.050	0.22	8.28	1.82	10.05	17.98	0.89	0.234	5.8	4.47	533.0	37.0	69.0	14.0	420.0	540.0
	2BC	62+	0.071	1.01	0.090	0.11	3.74	0.70	6.15	8.24	0.71	0.159	5.6	4.10	223.0	27.0	46.0	18.0	134.0	225.0
C05	A	13	0.878	13.85	0.110	0.77	16.97	3.94	26.99	45.20	0.84	0.353	5.5	4.70	1384.0	136.0	65.0	50.0	191.0	1442.0
	2Bt	31	0.273	3.61	0.090	0.33	3.84	0.81	18.06	19.15	1.01	0.356	5.0	3.73	680.0	62.0	84.0	26.0	520.0	692.0
	2Cox	85+	0.103	1.52	0.090	0.32	2.83	0.00	10.42	10.57	0.75	0.176	5.0	3.69	355.0	35.0	70.0	44.0	209.0	358.0
										Satanta Peak till deposits, outer moraine, 10-12 ka										
C06	A	15	0.819	13.34	0.060	0.32	21.72	3.63	18.7	43.04	0.75	0.374	6.0	5.41	1106.0	108.0	57.0	16.0	971.0	1152.0
	2Bt	38	0.189	2.09	0.090	0.03	2.93	0.00	12.91	13.40	0.72	0.261	5.2	3.91	417.0	43.0	50.0	12.0	317.0	422.0
	2Cox	80+	0.041	0.48	0.050	0.02	1.41	0.00	4.42	3.91	0.51	0.119	5.3	4.02	196.0	25.0	75.0	28.0	69.0	197.0
C07	A	11	0.744	12.33	0.080	0.75	12.42	2.43	23.17	36.55	0.73	0.313	5.1	4.31	858.0	109.0	62.0	21.0	697.0	889.0
	2AB	16	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
	2Bw	41	0.138	1.51	0.080	0.02	2.63	0.00	9.29	10.32	0.86	0.224	5.0	3.81	280.0	41.0	84.0	8.0	150.0	283.0
	2Cox	80+	0.031	0.34	0.090	0.02	1.82	0.00	5.27	4.74	0.54	0.166	5.3	4.05	166.0	43.0	64.0	27.0	33.0	167.0
C08	A	9	nd	10.00	0.060	0.71	10.81	2.12	13.87	26.31	1.06	0.419	nd	nd	nd	112.0	109.0	26.0	277.0	1524.0
	2Bw	25	0.112	1.44	0.050	0.06	2.52	0.00	7.76	8.74	0.89	0.220	5.1	3.89	337.0	31.0	80.0	5.0	224.0	340.0
	2Cox	85+	nd	0.44	0.030	0.09	2.32	0.00	3.98	3.58	0.71	0.231	nd	nd	nd	36.0	74.0	41.0	64.0	215.0

[1] Chemical analyses were performed on the less than 2 mm size fraction of the soil samples.
[2] Soil-profile sites are shown on figure 2.
[3] Chemical data are for the combined Cox horizons.
[4] The forms of phosphorus are: Pt, total; Pnoc, non-occluded; Poc, occluded; Pca, acid-extractable calcium-bound; Po, organic.

Supplementary table 4. Clay mineralogy

[Relative abundances of clay minerals based on peak height: n, none detected; +, minor amount; ++, moderate amount; +++, major amount; ++++, dominant amount. na, sample not analyzed. Analysts: A. Busacca, P. Janitsky, R. Meixner, under M. Singer, University of California, Davis]

Site[1]	Horizon	Basal depth (cm)	Chlorite	Kaolinite	Smectite	Mica	Vermiculite[2]	Interstratified[3]
				Gannett Peak till deposits, 0.1-0.35 ka				
C02	A	0.5	++	+++	++	+++	+	n
	Cox	3	na	na	na	na	na	na
	Cu	18+	++	++++	++	++++	+	n
				Audubon rock-glacier deposits, 0.95-2.4 ka				
C01	A	7	+	++++	++++	++	+	n
	AC	27	+	+++	++++	++	n	n
	Cox	47	+	+++	++++	++	n	n
	Cox	75+	+	+++	++++	++	n	n
				Triple Lakes rock-glacier deposit, 3-5.2 ka				
C03	A	12	+	++	+++	++	n	n
	2A	24	+	+++	+++	++	n	n
	2Bw	29	+	+++	++++	++	n	+
	2Cox	58+	+	++++	++++	++	n	n
				Satanta Peak till deposits, inner moraine, 10-12 ka				
C04	A	14	+	++	+++	++	n	n
	2Bt	38	+	+++	++++	+	n	+
	2BC	62+	+	++	+++	+	n	+
C05	A	13	+	++	++	++	n	n
	2Bt	31	+	++	++	+	n	+
	2Cox	85+	+	++	++	+	n	n
				Satanta Peak till deposits, outer moraine, 10-12 ka				
C06	A	15	+	++	++	+	n	+
	2Bt	38	+	++	++++	+	n	+
	2Cox	80+	+	++	++	+	n	+
C07	A and 2AB	16	+	++	++	+	n	n
	2Bw	41	+	++	++	+	n	+
	2Cox	80+	+	++	+	+	n	+
C08	A	9	+	++	+++	++	n	n
	2Bw	25	+	++	++	+	n	+
	2Cox	85+	+	+++	+	++	n	+

[1]Soil-profile sites are shown on figure 2.
[2]Vermiculite may be present, but not detectable in some samples; however, most samples showed no increase in intensity of the 1-nm peak after saturation with KCl.
[3]Interstratified clay minerals are chiefly regularly interstratified mica-chlorite; some interstratified mica-vermiculite may also be present.

Supplementary table 5. Total chemical analyses of the soils (less than 0.05 mm fraction) determined by X-ray fluorescence spectroscopy

[na, sample not analyzed; nd, not determined, units in weight percent. Analysts: J. Baker, J. Taggart, J.S. Wahlberg, U.S. Geological Survey, Menlo Park]

Site[1]	Horizon	Basal depth (cm)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
					Gannett Peak till deposits, 0.1-0.35 ka							
C02	A	0.5	53.40	23.60	8.850	2.20	0.650	0.90	2.94	0.82	0.1	0.06
	Cox	3	na	na	na	na	na	na	na	na	na	na
	Cu	18+	51.80	26.80	8.350	3.10	0.570	0.90	3.83	0.90	0.1	0.09
					Audubon rock-glacier deposits, 0.95-2.4 ka							
C01	A	7	54.40	21.10	6.060	1.80	0.690	0.80	2.71	0.71	0.2	0.08
	AC	27	53.30	23.80	6.620	2.00	0.590	0.80	2.90	0.71	0.2	0.10
	Cox	47	52.50	26.90	6.930	2.00	0.510	0.80	3.06	0.69	0.1	0.09
	Cox	75+	53.20	24.20	8.940	2.20	0.510	0.90	3.31	0.85	0.1	0.08
					Triple Lakes rock-glacier deposit, 3-5.2 ka							
C03	A	12	na	na	na	na	na	na	na	na	na	na
	2A	24	50.70	18.90	5.750	1.80	0.690	0.90	2.53	0.71	0.5	0.08
	2Bw	49	56.20	20.30	6.940	1.90	0.660	1.10	2.84	0.81	0.2	0.09
	2Cox	58+	47.00	21.60	8.810	2.20	0.480	0.80	3.19	1.11	0.2	0.05
					Satanta Peak till deposits, inner moraine, 10-12 ka							
C04	A	14	53.40	16.40	5.290	1.40	1.060	1.00	2.44	0.64	0.3	0.06
	2Bt	38	55.30	18.00	5.600	1.50	0.680	0.80	2.35	0.87	0.3	0.03
	2BC	62+	47.50	21.90	8.580	2.00	0.180	0.70	2.11	0.79	0.2	0.04
C05	A	13	na	na	na	na	na	na	na	na	na	na
	2Bt	31	46.90	19.00	6.970	1.60	0.440	0.80	2.54	0.93	0.3	0.04
	2Cox	85+	52.70	27.40	6.020	2.30	0.440	0.80	3.03	0.63	0.1	0.09
					Satanta Peak till deposits, outer moraine, 10-12 ka							
C06	A	15	49.00	11.90	3.880	1.30	1.320	1.00	2.19	0.61	0.4	0.05
	2Bt	38	54.60	18.00	5.250	1.30	0.410	0.80	2.32	0.82	0.2	0.04
	2Cox	80+	na	na	na	na	na	na	na	na	na	na
C07	A	11	na	na	na	na	na	na	na	na	na	na
	2AB	16	na	na	na	na	na	na	na	na	na	na
	2Bw	41	49.80	22.30	8.310	2.00	0.390	0.80	2.98	0.85	0.2	0.04
	2Cox	80+	52.60	24.40	8.380	2.40	0.350	0.80	3.57	0.90	0.1	0.06
C08	A	9	50.80	12.80	4.500	1.40	0.960	1.00	2.35	nd	0.4	0.05
	2Bw	25	50.20	21.60	8.180	1.90	0.450	0.80	2.63	0.89	0.2	0.03
	2Cox	85+	51.00	24.80	8.480	2.40	0.370	0.80	3.55	0.94	0.1	0.05

[1] Soil-profile sites shown on figure 2.

Supplementary table 6. Total chemical analyses of the soils (less than 0.05 mm fraction) determined by instrumental neutron activation

[na, not analyzed; Na, Fe, and K values in weight percent, all others in part per million. Analysts: J. Budahn, R. Knight under D.M. McKown, U.S. Geological Survey, Menlo Park]

Site[1]	Horizon	Basal depth (cm)	Na	Nd	Rb	Sb	Sc	Sm	Sr	Ta	Tb	Th	Tm	U	Yb	Zr	Ba	Co	Cr	Cs	Dy	Eu	Fe	Gd	Hf	K	La	Lu	Mn
Gannett Peak till deposits, 0.1-0.35 ka																													
C02	A	0.5	0.699	91.5	154.0	0.421	17.60	17.20	100.0	0.834	1.810	37.7	0.75	7.24	4.68	589.0	508.0	19.00	150.0	3.54	10.10	2.200	5.94	12.20	17.20	2.41	100.0	0.721	524.0
	Cox	3	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
	Cu	18+	0.644	64.4	225.0	0.000	25.60	11.50	0.0	0.975	1.200	26.5	0.48	6.08	2.77	410.0	619.0	27.80	154.0	4.85	6.64	1.680	5.99	9.70	10.70	3.17	68.0	0.441	728.0
Audubon rock-glacier deposits, 0.95-2.4 ka																													
C01	A	7	0.681	66.4	134.0	0.788	14.10	11.30	100.0	0.864	1.190	26.5	0.56	7.86	3.39	433.0	478.0	14.60	96.0	4.80	7.29	1.610	4.03	7.82	12.80	2.21	68.5	0.513	658.0
	AC	27	0.596	64.1	152.0	0.397	16.60	12.00	100.0	0.883	1.250	27.9	0.55	9.86	3.31	418.0	484.0	17.80	111.0	5.60	6.83	1.640	4.63	9.11	12.30	2.28	68.8	0.489	768.0
	Cox	47	0.552	74.5	169.0	0.209	18.10	13.60	100.0	0.762	1.430	31.8	0.56	10.70	3.53	475.0	470.0	19.60	116.0	4.95	8.09	1.840	4.75	9.32	13.50	2.50	77.6	0.513	735.0
	Cox	75+	0.541	85.2	170.0	0.093	19.40	15.50	0.0	0.798	1.660	36.3	0.58	11.20	3.50	339.0	505.0	21.50	138.0	4.48	8.69	2.010	6.19	12.30	9.79	2.64	89.5	0.497	671.0
Triple Lakes rock-glacier deposit, 3-5.2 ka																													
C03	A	12	0.639	49.9	149.0	0.491	11.20	8.57	106.0	0.803	0.918	21.5	0.47	5.70	2.91	352.0	494.0	11.10	75.6	4.17	5.35	1.160	3.22	7.90	9.85	1.91	52.5	0.447	635.0
	2A	24	0.651	54.0	152.0	0.483	14.30	9.79	100.0	0.977	1.100	24.4	0.59	6.54	3.65	387.0	481.0	13.90	94.1	5.00	6.56	1.380	4.01	7.44	11.50	2.15	57.0	0.532	677.0
	2Bw	49	0.725	63.4	153.0	0.281	15.50	12.20	143.0	0.902	1.320	29.6	0.00	6.54	4.20	411.0	491.0	16.20	107.0	4.53	7.50	1.580	4.77	8.40	11.90	2.34	71.1	0.623	707.0
	2Cox	58+	0.678	65.5	226.0	0.140	18.90	11.20	140.0	1.280	1.030	31.8	0.55	6.25	3.29	475.0	519.0	18.60	154.0	5.28	6.05	1.400	6.03	7.27	14.90	2.62	66.0	0.498	434.0
Satanta Peak till deposits, inner moraine, 10-12 ka																													
C04	A	14	0.765	59.2	123.0	0.417	10.70	10.80	105.0	0.776	1.170	25.2	0.56	6.41	3.53	499.0	486.0	11.20	97.6	3.51	6.75	1.440	3.60	7.55	13.80	2.11	64.2	0.535	471.0
	2Bt	38	0.626	42.9	188.0	0.443	12.00	7.68	100.0	1.160	0.866	17.4	0.48	5.10	3.01	410.0	464.0	9.80	85.7	7.00	5.23	1.110	3.78	5.81	11.60	1.85	47.5	0.470	324.0
	2BC	62+	0.465	65.8	157.0	0.150	17.90	11.60	100.0	0.764	1.290	27.8	0.57	5.59	3.48	538.0	471.0	19.10	136.0	5.40	7.22	1.570	6.03	9.13	15.10	2.13	71.1	0.547	401.0
C05	A	13	0.661	34.7	135.0	0.531	9.09	6.37	118.0	0.761	0.723	16.3	0.00	4.21	2.29	295.0	439.0	8.87	60.8	3.76	4.32	0.935	2.75	4.97	8.56	1.87	40.6	0.361	356.0
	2Bt	31	0.554	50.8	185.0	0.296	14.70	8.63	110.0	1.180	0.892	23.0	0.00	4.98	3.50	458.0	454.0	13.20	105.0	4.96	5.10	1.130	4.77	6.27	13.30	2.05	54.8	0.504	324.0
	2Cox	85+	0.54	48.8	182.0	0.140	19.60	8.79	100.0	0.800	0.916	20.6	0.00	5.39	2.84	374.0	473.0	19.80	104.0	5.12	5.48	1.340	4.30	6.02	10.90	2.39	52.9	0.452	723.0
Satanta Peak till deposits, outer moraine, 10-12 ka																													
C06	A	15	0.696	37.4	127.0	0.651	8.62	6.52	150.0	0.909	0.796	15.6	0.43	4.27	2.72	342.0	471.0	8.63	55.7	4.65	4.86	1.040	2.77	5.22	9.59	1.71	41.0	0.437	406.0
	2Bt	38	0.651	50.2	191.0	0.396	12.00	8.74	100.0	1.130	1.020	21.3	0.59	5.03	3.59	517.0	499.0	10.30	80.9	6.20	5.91	1.300	3.83	6.22	13.00	1.84	55.1	0.581	376.0
	2Cox	80+	0.675	81.9	161.0	0.099	18.00	14.90	100.0	0.954	1.650	37.4	0.84	6.55	4.65	613.0	512.0	19.00	127.0	4.40	9.27	1.920	5.78	10.30	17.30	2.38	91.5	0.735	454.0
C07	A	11	0.665	43.2	123.0	0.458	9.84	8.18	117.0	0.837	0.887	19.5	0.43	4.22	2.76	334.0	425.0	9.79	66.4	3.92	5.31	1.110	3.11	6.35	8.98	1.66	50.5	0.430	427.0
	2AB	16	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
	2Bw	41	0.592	69.1	169.0	0.140	17.80	12.50	120.0	0.907	1.300	31.2	0.61	5.26	3.85	490.0	499.0	16.70	119.0	4.14	7.91	1.550	5.67	10.20	13.80	2.41	76.8	0.592	349.0
	2Cox	80+	0.675	70.4	197.0	0.099	20.70	12.20	100.0	0.958	1.250	32.2	0.55	5.10	3.63	412.0	581.0	22.10	136.0	4.17	7.71	1.550	5.93	10.30	12.00	2.99	75.1	0.560	504.0
C08	A	9	0.738	46.8	119.0	0.628	9.44	8.39	130.0	0.953	0.918	21.2	0.50	5.14	3.18	424.0	474.0	8.55	59.8	4.46	5.48	1.160	3.12	6.38	11.90	1.90	53.7	0.499	381.0
	2Bw	25	0.645	84.5	155.0	0.130	17.40	15.10	100.0	1.050	1.480	36.2	0.85	6.71	4.72	576.0	494.0	15.40	124.0	4.05	9.28	1.710	5.74	11.10	17.40	2.33	89.5	0.755	342.0
	2Cox	85+	0.663	64.5	192.0	0.000	21.10	11.70	100.0	1.070	1.380	32.3	0.66	4.87	4.31	452.0	546.0	22.30	138.0	4.25	7.60	1.510	5.92	9.24	13.40	2.89	73.7	0.658	478.0

[1] Soil-profile sites are shown on figure 2.

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