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Integrating soils and geomorphology in mountains—an example from the Front Range of Colorado

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Abstract

Soil distribution in high mountains reflects the impact of several soil-forming factors. Soil geomorphologists use key pedological properties to estimate ages of Quaternary deposits of various depositional environments, estimate long-term stability and instability of landscapes, and make inferences on past climatic change. Once the influence of the soil-forming factors is known, soils can be used to help interpret some aspects of landscape evolution that otherwise might go undetected.

The Front Range of Colorado rises from the plains of the Colorado Piedmont at about 1700 m past a widespread, dissected Tertiary erosion surface between 2300 and 2800 m up to an alpine Continental Divide at 3600 to over 4000 m. Pleistocene valley glaciers reached the western edge of the erosion surface. Parent rocks are broadly uniform (granitic and gneissic). Climate varies from 46 cm mean annual precipitation (MAP) and 11 °C mean annual temperature (MAT) in the plains to 102 cm and −4 °C, respectively, near the range crest. Vegetation follows climate with grassland in the plains, forest in the mountains, and tundra above 3450 m. Soils reflect the bioclimatic transect from plains to divide: A/Bw or Bt/Bk or K (grassland) to A/E/Bw or Bt/C (forest) to A/Bw/C (tundra). Corresponding soil pH values decrease from 8 to less than 5 with increasing elevation. The pedogenic clay minerals dominant in each major vegetation zone are: smectite (grassland), vermiculite (forest), and 1.0–1.8 nm mixed-layer clays (tundra). Within the lower forested zone, the topographic factor (aspect) results in more leached, colder soils, with relatively thin O horizons, well-expressed E horizons and Bt horizons (Alfisol) on N-facing slopes, whereas soils with thicker A horizons, less developed or no E horizons, and Bw or Bt horizons (Mollisol) are more common on S-facing slopes. The topographic factor in the tundra results in soil patterns as a consequence of wind-redistributed snow and the amount of time it lingers on the landscape. An important parent material factor is airborne dust, which results in fine-grained surface horizons and, if infiltrated, contributes to clay accumulation in some Bt horizons. The time factor is evaluated by soil chronosequence studies of Quaternary deposits in tundra, upper forest, and plains grassland. Few soils in the study area are >10,000 years old in the tundra, >100,000 years old in the forest, and >2 million years old in the grassland. Stages of granite weathering vary with distance from the Continental Divide and the best developed is *grus* near the sedimentary/granitic rock contact just west of the mountain front. *Grus* takes a minimum of 100,000 years to form.

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Some of the relations indicated by the soil map patterns are: (1) parts of the erosion surface have been stable for 100,000 years or more; (2) development of *grus* near the mountain front could be due in part to pre-Pennsylvanian weathering; (3) a few soil properties reflect Quaternary paleoclimate; and (4) a correlation between soil development in the canyons and stream incision rates.

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1. Introduction

Soils can provide information useful to the geomorphological interpretation of mountainous terrain. Their distribution, laterally and vertically, results from the impact of the soil-forming factors—climate, vegetation, topographic setting, parent material, and time (Jenny, 1980; Birkeland, 1999). The altitudinal distribution of soils shows the impact of the climate and vegetation factors. One of the more important roles of soils is in helping put surficial deposits of diverse origins (glacial, fluvial, colluvial, periglacial, etc.—the parent material factor) into age groups (time factor). Richmond (1962) did this in his classic work in the La Sal Mountains of Utah. The topographic factor needs more study, because if there are marked differences in soils with topographic setting, one has to determine if it is due to the time factor or to the rates of pedological processes.

This paper analyses the relation between soils and geomorphology in the Front Range of Colorado and adjacent plains. Birkeland studied the area in a reconnaissance fashion while taking students on field trips for the past 35 years. Former students and colleagues have contributed by their detailed published and unpublished work on parts of the range and plains. However, this study—a first approximation of a coherent soil-geomorphic history of the range—was facilitated by soil maps and profile descriptions for the Front Range west of Boulder by the U.S. Department Agriculture, U.S. Forest Service (2001, and written communications, 1999, respectively).

There are not many examples of integrating soils and geomorphology at the scale of a mountain range. One exception is the work of Tonkin and Basher (1990) in the Southern Alps of New Zealand. Soil distribution was well known from extensive mapping, and they did detailed studies in key basins across the range. Uplift, precipitation, and erosion rates all

increase from east to west, and relate well to the soil patterns. In the eastern part of the range, mean annual precipitation (MAP) is relatively low (<100 cm), uplift and erosion slight, and A/Bw/C soil profiles on transport-limited slopes denote geomorphic stability during most of the Holocene. In areas with MAP between 140 and 200 cm, the soil pattern is complex and consists of both eroded soils in the upper parts of the basins and one or more buried soils in the lower parts. In contrast, in the western part of the range, a high uplift rate combined with >1000 cm MAP results in high erosion rates, A/R soil profiles on steep weathering-limited slopes, and soil residence times of 100–200 years.

A few of the lessons learned in Southern Alps apply to the Front Range of Colorado. One is that the precipitation in the latter area is similar to that of the drier part of the Southern Alps study area, and the landscape and soils in the Front Range of Colorado seem similarly relatively stable. A second is that basin-wide patterns of soil development seem to correspond with stream incision rates.

2. Regional setting

The Front Range of Colorado rises abruptly above the Colorado Piedmont section of the Great Plains (Fig. 1). This paper focuses on a Colorado Piedmont-to-Front Range of Colorado transect near the town of Boulder. The base of the mountain front is between 1700 and 1830 m, and the area west of the front rises to about 2500 m over a distance of about 6 km. Farther west are remnants of a dissected Tertiary erosion surface (Scott and Taylor, 1986; Bradley, 1987). This surface is expressed by accordant ridges and extensive areas of low-relief terrain that slope gently upward to the west to about 2750 m over distances of about 10–20 km. West of the erosion

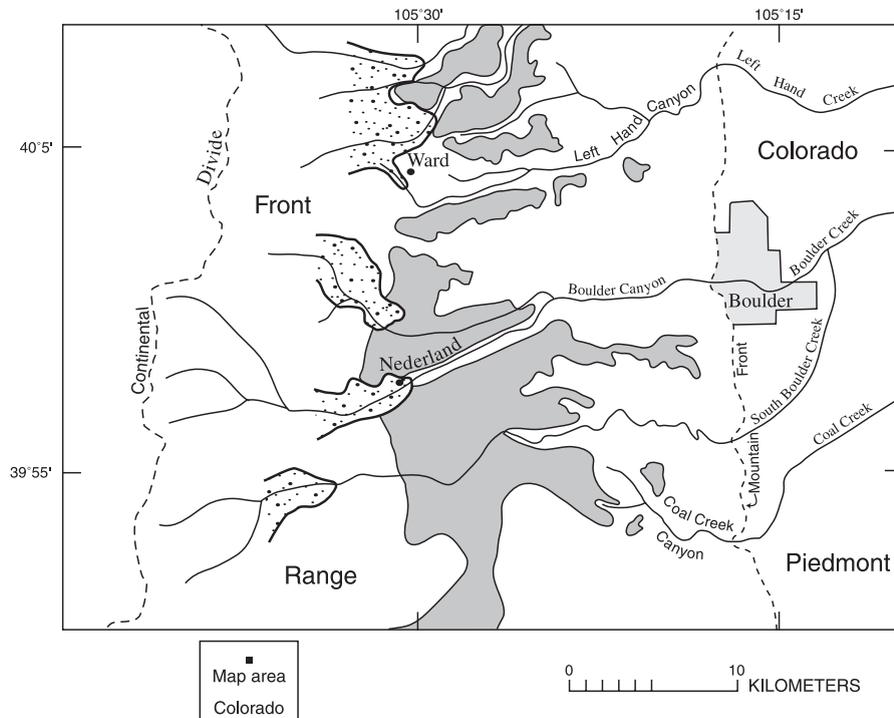


Fig. 1. Location map showing the Front Range of Colorado, mountain front, and Colorado Piedmont near Boulder, Colorado. Heavy solid lines near Ward and Nederland indicate the approximate lower limit of Pleistocene glaciation; dotted pattern indicates till and related glacial deposits (modified from Madole et al., 1998). Gray pattern shows the approximate extent of a Tertiary erosion surface (modified from Scott and Taylor, 1986).

surface, the mountains rise to the Continental Divide (3600–4100 m) over distances of about 10–15 km.

Several rivers drain the area. To the south is Coal Creek, which heads about 28-km east of the Continental Divide; its headwaters were never glaciated. To the north, both Boulder and Left Hand Creeks head just east of the Continental Divide and their upper reaches were glaciated during the Pleistocene. Boulder Creek was more extensively glaciated. The glaciers in both of these drainages terminated at about 2500–2700 m, close to the western edge of the erosion surface. All of the above creeks flow in steep-sided canyons; canyon relief is high in the glaciated mountains, minor near the western edge of the erosion surface, and increases to a maximum just west of the mountain front. Maximum relief in the canyons is Coal Creek, 660 m; Boulder Creek, 840 m; and Left Hand Creek, 350 m.

There is disagreement regarding the elevation at which the erosion surface formed—did it form close

to its present elevation, or did it form at a lower elevation and subsequently been uplifted (Steven et al., 1997 and references cited therein). Whatever the case, canyon cutting commenced about 5 my (million years) ago (Trimble, 1980; Steven et al., 1997).

3. Soil profiles

Soil profiles are composed of various horizons, and the kind of soil profile varies with the soil-forming factors (Birkeland, 1999). The surface O and A horizons are commonly high in organic matter and have characteristically dark colors. Beneath the O and (or) A, mostly in acidic forested conditions, is a light colored E horizon. The color of the latter horizon indicates that much of the iron released in it has been translocated to the underlying B horizon. Beneath the A and (or) E horizons in most environments, given sufficient time for them to develop, is a B horizon.

There are several types of B horizons. A Bw horizon in this area is generally oxidized. An example would be a parent material of 2.5Y hue alters to a Bw with a 10YR hue. The alteration is due to Fe release during weathering. Given sufficient time, clay accumulation is recognizable, and the horizon is designated Bt. The clay has either infiltrated from overlying horizon(s) or formed in place. In drier moisture regimes (grasslands in the plains of this study), soil moisture is insufficient to leach carbonate from the soil, and it accumulates to form Bk or K horizons; these horizons form beneath the Bw or Bt, or can occur as an overprint on the Bt horizon (e.g., Btk). Six morphological stages in the development of carbonate horizons are recognized in the western USA, and the time to attain each stage varies with climate and the rate of influx of Ca-enriched dust (Machette, 1985). The first two stages (I and II) are Bk horizons in which the color of the non-carbonate material is clearly visible. If carbonate accumulation is extensive and the carbonate and its white color dominate the horizon, the horizon is designated K (stages III through VI). At depth is the little altered surficial parent material referred to as the C horizon (Cox if slightly altered and Cu if unaltered). Rock parent material is designated R, Cr if the rock is weathered, and Crt if clay has accumulated. Horizons with evidence of gleying are designated by the letter g (e.g., Bg). In Canada (Soil Classification Working Group, 1998), if a particular type of horizon is so

weakly developed that it barely meets the criteria for its recognition, it is followed by the letter j (e.g., Ej or Btj), a practice we have adopted.

4. Factors of soil formation, Front Range of Colorado

Jenny (1980) formulated the general soil-forming equation

$$\text{Soil} = f(\text{cl, o, r, p, t, } \dots)$$

where cl is climate, o organisms, primarily vegetation, r slope or topographic setting, p parent material, t time over which the soil has formed, and ... unknown factors, a common one important to this study is airborne dust. Each factor has a strong influence on the resulting soil, and knowledge of these factors can be used to predict the soil properties at a particular site.

Climate and vegetation vary with altitude in the study area transect (Fig. 2). The Colorado Piedmont is warm and dry with grassland vegetation. Westward into the mountains, the mean annual temperature progressively decreases, MAP increases, and the vegetation varies accordingly. Most of the range is in forest, except for tundra above about 3450 m.

Bedrock parent material in much of the mountains consists of a Precambrian core of igneous and high-

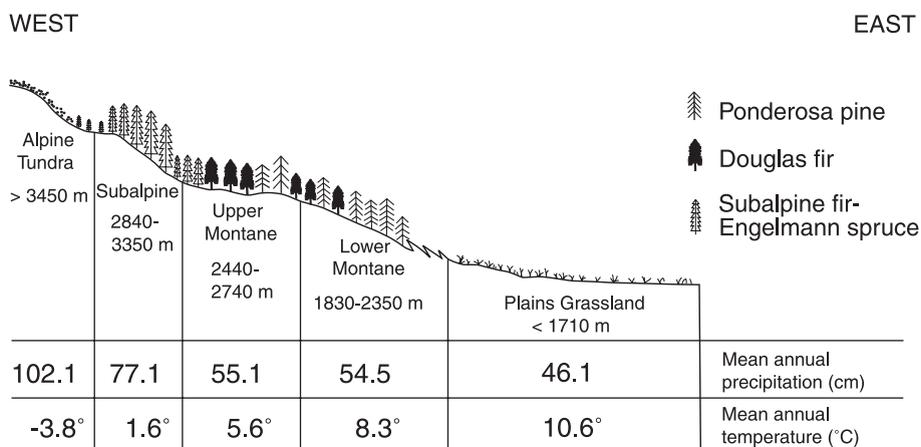


Fig. 2. Vegetation zones and climatic data for a transect from the Continental Divide to the Colorado Piedmont near Boulder (modified from Veblen and Lorenz, 1991, Fig. 2, and Barry, 1973, Table 4 and p. 92). Elevation ranges are typical for the vegetation zones. Gaps between adjacent elevation ranges represent ecotones between the zones.

grade metamorphic rocks (Lovering and Goddard, 1950; Tweto, 1979; Braddock and Cole, 1990). The oldest rocks (>1.7 by [billion years] old) are biotite and hornblende gneiss and schist; these were intruded by granodiorite (1.7 by) and granite (1.4 by). Small intrusive bodies of Tertiary age (mainly monzonite and quartz monzonite) comprise a minor amount of the igneous rocks. The Colorado Mineral Belt of Tertiary mineralization trends NE–SW through the area and intersects the range front north of Boulder; hydrothermal alteration of the bedrock within this belt is common. A narrow outcrop of E-dipping sedimentary rocks veneers the front of the range, and shale commonly underlies the Quaternary fluvial and other surficial deposits in the plains.

The parent material for most soils discussed here formed from rocks and surficial deposits high in feldspar, quartz, biotite, and hornblende. Most of the deposits are gravelly with a sandy matrix, except for loess caps that are high in silt.

The ages of the soils throughout the study area can be estimated from stratigraphic and geochronologic studies in both the plains and mountains. A well-expressed suite of river terrace deposits in the plains (Fig. 3) is dated and correlated by the radiocarbon and uranium-series methods, association with volcanic ash of known age, soils, and relative height above streams. The lower terrace deposits are generally accepted as having been deposited during the Holocene and the Pinedale and Bull Lake glaciations (Madole, 1991).

There is less agreement on the climatic control and the timing of the older surficial deposits. The oldest widespread deposit, the Rocky Flats Alluvium, is about 2 Ma (million years old) (Birkeland et al., 1996). The older mountain chronosequence is formed in two widespread deposits—till of the Pinedale glaciation (younger, and associated with marine isotope stages 2 and 4) and till of the Bull Lake glaciation (mainly marine isotope stage 6). They are dated and correlated by the radiocarbon method, cosmogenic isotope exposure age estimates, soils, and rock-weathering features (Madole, 1986; Madole and Shroba, 1979; Madole et al., 1998; Nelson and Shroba, 1998; Schildgen, 2000). Pertinent local ages are a radiocarbon age of 23.5 ky (thousand years old) for the maximum extent of Pinedale ice, and a minimum cosmogenic isotope exposure age of 122 ky for the maximum extent of Bull Lake ice. A younger mountain chronosequence is formed in rock-glacier deposits and in tills deposited by glaciers that re-occupied cirques after the disappearance of Pinedale ice. The oldest post-Pinedale till is about 12 ky (possible Younger Dryas equivalent), and there are at least three younger Holocene advances. Dating and correlating of these deposits are by the radiocarbon method, lichenometry, soils, and rock-weathering features (Benedict, 1985; Birkeland et al., 1987; Davis et al., 1992).

There are few data on the influence of topographic setting on soil development in the study area, as all the soil chronosequence study sites were on relatively flat

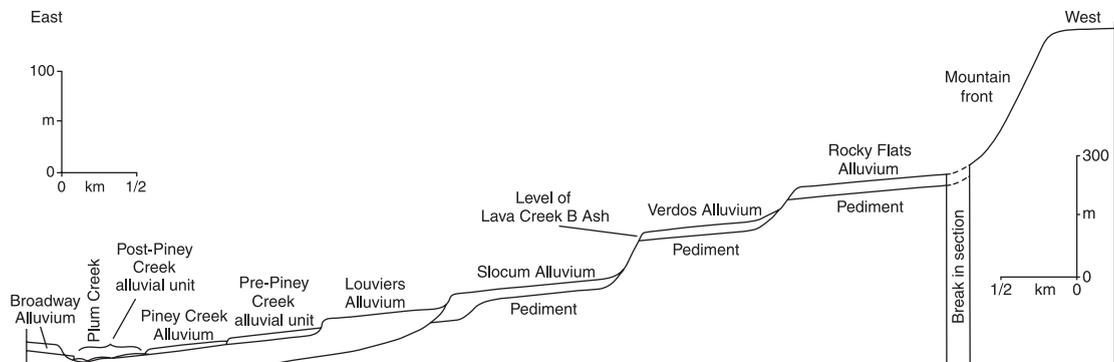


Fig. 3. Diagrammatic cross-section of alluvial units in the Colorado Piedmont near Denver (from Madole, 1991, Fig. 14). Approximate ages are: post-Piney Creek, Piney Creek, and pre-Piney Creek alluvial units, Holocene; Broadway Alluvium, Late Pleistocene (Pinedale glaciation); Louviers Alluvium, Late Pleistocene, or late Middle Pleistocene (Bull Lake glaciation); Slocum Alluvium, 240 ky; Verdos Alluvium, similar to age of intercalated Lava Creek B ash, 640 ky; Rocky Flats Alluvium, about 2 Ma.

surfaces. However, catena studies on Holocene and Pleistocene moraines in other parts of the Rocky Mountains serve as a model of soil development on slopes with time (Birkeland, 1999, p. 247). Aspect influences soil development in the canyons because they trend E–W, and the bioclimatic zones in the canyons are strongly influenced by aspect. At any given elevation, the S-facing slopes are relatively warm, and the N-facing cool, and these differences are reflected in the vegetation (Veblen and Lorenz, 1991).

5. General soil distribution, Front Range of Colorado

The general soil pattern of the study area reflects the impact of the above soil-forming factors (U.S. Department Agriculture, Soil Conservation Service, 1975, with changes that correspond with the most recent Soil Taxonomy, Soil Survey Staff, 1999). Argiustolls and Paleustolls (A/Bw or Bt/Bk or K/C profiles) dominate in the plains. The forested mountains are mainly Cryalfs (cold soils with A/E/Bt/C profiles) at higher elevations and Ustalfs at lower elevations. Cryepts (cold soils with A/Bw/C profiles) are above tree line. Soil pH decreases with elevation from about 8 in the grasslands to 5 and less in the tundra (Netoff, 1977, written communication 1970; Birkeland et al., 1987). There are a wide variety of clay minerals in the soils of the study area. Clays that are best associated with the overall bioclimate and geochemical conditions are smectite in the plains, vermiculite in the forest, and mixed layer 1.0–1.8-nm clays above tree line (Netoff, 1977; Shroba and Birkeland, 1983; Birkeland et al., 1987).

6. Soil chronosequences

We have studied soil chronosequences in three major vegetation zones—the grasslands using mainly fluvial deposits about 2 Ma and younger, the upper montane using tills of the Pinedale and Bull Lake glaciations (about 14–47 and 120–160 ky, respectively; Nelson and Shroba, 1998), and in the alpine tundra using tills and rock-glacier deposits 12 ky and younger.

6.1. Grassland soil chronosequence

Birkeland et al. (1996) provide the latest review of soils in the plains, much of which is based on the quantitative studies by Machette (1975, 1977, 1985) and Machette et al. (1976).

A characteristic soil sequence is present throughout the plains of the study area (Fig. 4); carbonate has accumulated in many of the soils and the morphological stages of development of these soils are from Machette (1985, Table 2). Soils formed in Holocene deposits (Piney Creek Alluvium and younger) are A/Cu profiles in the youngest deposit, and A/Bw/C with or without a Bk in the older deposits. Overthickened (cumulic) A horizons, due to pedogenesis keeping pace with floodplain sedimentation, are common. Some of these latter A horizons are several times thicker than the typical (noncumulic) A horizons. Soils in Broadway Alluvium (Pinedale age) have A/Bw/C profiles on coarse-grained alluvium, but A/Bt/Bk profiles on fine-grained (silty) alluvium. Carbonate morphology is stage I in post-Broadway and younger soils. Morphological differences with grain size are a good example of the effect of the parent material factor, as soils formed from the finer-grained (silty) materials have sufficient primary clay for soil water to redistribute it downward to form a Bt horizon, and the slight decrease in permeability is sufficient to cause carbonate to precipitate rather than be carried in solution through the soil. Soils formed in loess considered to be the same age as the Broadway Alluvium also have an A/Bt/Bk profile (Reheis, 1980). Soils formed in Louviers Alluvium (Bull Lake age) have an A/Bt/Bk profile with stage II–III carbonate morphology. Soils in older alluvial deposits are progressively thicker, redder, more clay rich (Fig. 5), and display higher stages of carbonate morphology. The soil in the Rocky Flats Alluvium (about 2 Ma) is about as clay rich, red (10R in the Bt horizon), and carbonate rich in the K horizon (94%) as any soil on Earth (Birkeland, 1999). Machette (1985) ranks the plains near Boulder as one of relatively low carbonate influx when compared to other areas in the western USA. Pre-Broadway loesses are not present in the study area either because they were deposited only in areas farther east (Muhs et al., 1999) or, if deposited, they were

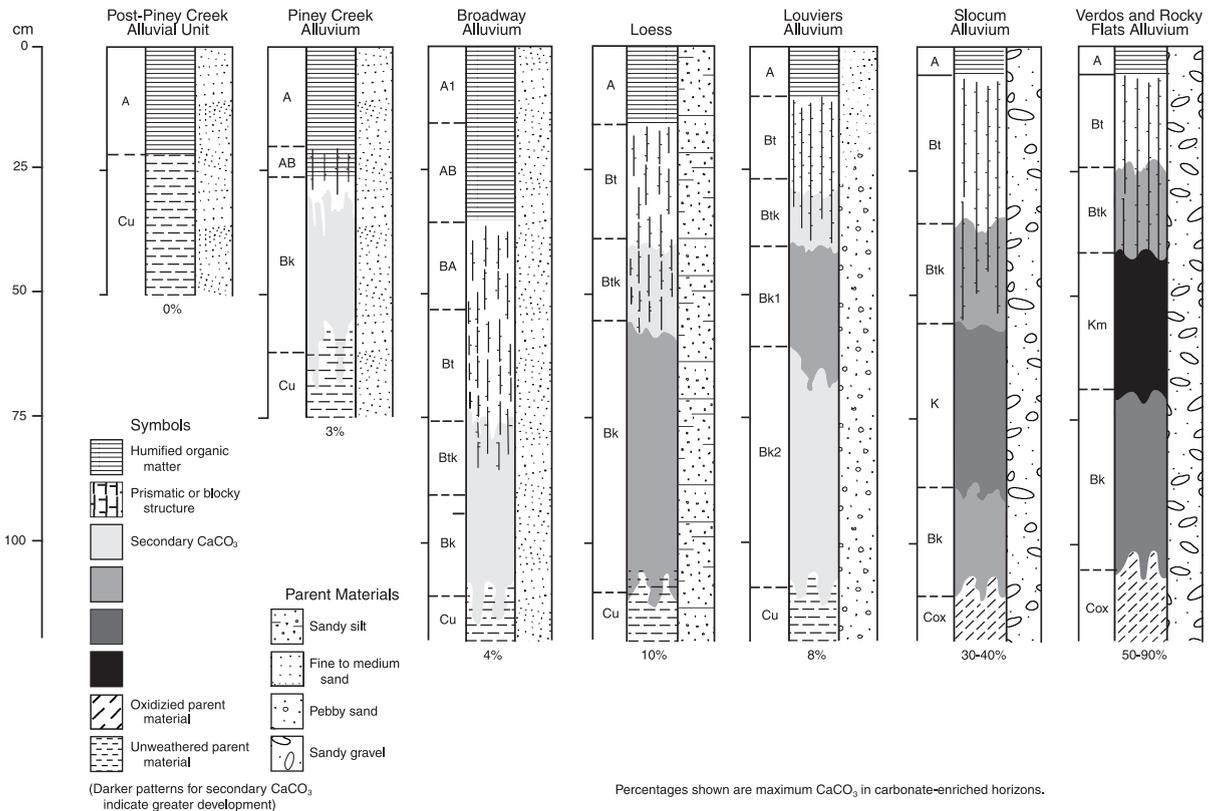


Fig. 4. Diagram showing maximum development of soils formed in alluvial units and loess (from Madole, 1991, Fig. 15). Although developed for the Lafayette area, Colorado (Machette, 1977), these soils are typical of those of the Colorado Piedmont in the Denver–Boulder area. Letters denote soil horizons.

locally incorporated into soils on pre-Broadway deposits (Shroba and Carrara, 1996), or were subsequently eroded.

The Rocky Flats Alluvium has an estimated age of about 2 Ma, based in large part on landscape position, minimum-limiting age of younger deposits, and buried soils (Machette et al., 1976; Birkeland et al., 1996). The nearby Verdos Alluvium is dated by its association with the Lava Creek B Ash (0.64 Ma; redated by Lanphere et al., 2002), and has an A/5YR Bt/stage III–IV K profile. The period of time between the deposition of the Verdos Alluvium and the Rocky Flats Alluvium is locally represented by at least seven buried soils. Using the morphology of the latter, their clay and carbonate contents, and the fact that both normal and reversed magnetic components are present in these soils, the age of the Rocky Flats is likely to be about 2 Ma.

6.2. Forest soil chronosequence

The forest chronosequence consists of soils formed in tills of the Pinedale and Bull Lake glaciations in the subalpine and upper montane forests, and therefore spans the last 120–160 ky (thousand years). Richmond (1960) did the early work on soils. In this study, we draw on the work by Madole (1969), Netoff (1977), Madole and Shroba (1979), Shroba and Birkeland (1983), and Madole et al. (1998).

The characteristic soil on till of the Pinedale glaciation has an O and (or) A/Ej or E/Bw or Btj/Cox profile. Hue of the B horizon is usually 10YR, and most of the clasts within the soil are unweathered. Clay content has a maximum content near 10% (< 2 mm-size fraction) and commonly decreases progressively with increasing depth. This distribution is thought to reflect the downward infiltration of airborne dust.

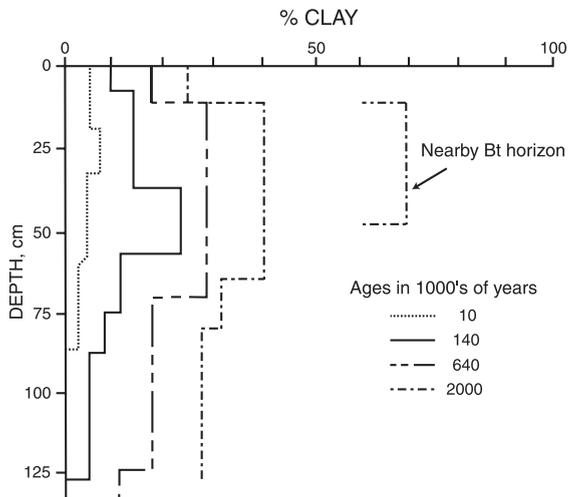


Fig. 5. Plot of clay content (<2 mm-size fraction) with depth in soils of the Colorado Piedmont in the Denver–Boulder area (from Machette, 1975, and Machette et al., 1976).

The characteristic soil on till of the Bull Lake glaciation is an O and (or) A/E/Bt/Cox profile. The Bt commonly has a 7.5YR hue, clay content reaches a maximum of 16%, and about 20% of biotite-rich granitic and gneissic clasts within the soil is weathered to *grus*. At one locality near Nederland, where there appears to be superimposed tills of the Pinedale and Bull Lake glaciations, the buried post-Bull Lake soil has a morphology similar to the above soil. We interpret this to mean that the major morphological features of the post-Bull Lake soil formed prior to the time when the Pinedale ice was close to its maximum extent. It is possible that much of this soil development occurred during the last interglacial period when climate over much of North America was warmer than the present (Muhs et al., 2002).

When one compares the soils younger than about 160 ky in the mountains with those of similar age in the plains, one sees many similarities in the relative development of B-horizon properties (e.g., clay content and color).

6.3. Alpine tundra soil chronosequence

The alpine chronosequence spans the time between about 0.3 and 12 ky (Mahaney, 1974; Benedict, 1985; Birkeland et al., 1987). Deposits that are 0.3 ky have a

thin A/Cu profile. Pedogenesis in increasingly older deposits results in an A/Cox/Cu profile in 2 ky, and an A/Bw/Cox profile in 3.5 ky with a maximum hue of 10YR. Soil color (chroma and value) is used to differentiate the Cox horizon from the Bw. The 12-ky soil has an A/Bw or Bt/Cox profile. The Bt horizons have a maximum clay content of 14%, double that of the underlying horizon, and most have a 7.5YR hue (versus 10YR for the Bw horizons).

Fine-grained material (fine sand and finer) is prominent in the A horizons of soils 2 ky and older. It is considered to be an eolian material mixed with the uppermost part of the underlying till or rock-glacier deposit. Geochemical data indicate that part of the fine-grained material is derived from semiarid basins upwind of the alpine soils (Muhs et al., 1992). Locally, it has been translocated and produces silt caps on clasts at depth (Burns, 1980) and contributes to the clay content in the Bt horizon.

Comparing the alpine and adjacent forest chronosequences, one sees that some 12-ky alpine tundra soils can be as well, or better, developed than 20-ky soils at lower elevations in the forest. Several factors that might help explain this are (1) greater eolian influx in the alpine, promoting greater availability of fines, (2) greater soil moisture in parts of the alpine due to wind redistribution of snow and the potential for melt-season flushing by large amounts of water through the soil and possibly (3) greater local disturbance of soils by tree throw in forested areas.

6.4. Soil catena chronosequences

Soil catena (toposequence) studies have not been undertaken on moraines in the Rocky Mountains of Colorado, but some have been done in other parts of the Rocky Mountains and western USA (reviewed by Birkeland, 1999, chapter 9). A soil catena consists of a number of soils aligned downslope on one landform to depict soil morphologies and properties at key slope positions. If these soils are on moraines of different ages, they constitute a soil catena chronosequence. These studies can provide age estimates for slopes and slope deposits throughout the Front Range of Colorado.

Although many of our catena studies were undertaken in sagebrush terrain in the western USA, Berry (1987) undertook one in the forested terrain in Idaho.

In general, the downslope soils have the same overall profile morphology as those upslope on the nearly flat moraine crest. In other words, the post-Pinedale soils have mainly Bw horizons at all slope positions, and most of the post-Bull Lake soils have Bt horizons at all slope positions. Downslope changes are least in the post-Pinedale soils, but in the post-Bull Lake soils, both the Bt clay content and clay maximum are more pronounced downslope and pedogenic Fe content parallels the clay content with depth.

In some catena studies in the western USA, the summit soil is the least developed of that catena. This is expected as soil moisture is least in the summit position. The relative development of some of the summit soils is so weak that we wondered if their weak development could be due in part to erosion. One possible answer came from a post-fire study of a forested catena in Wild Basin (McMillan, 1990), about 35 km northwest of Boulder. The summit soil in burned areas has an A/Cox/Cu profile, whereas the downslope soils have A/E/Bw/Cox profiles. Erosion, even on nearly flat surfaces, was widespread in burned areas and over time could help explain these contrasting soils with catena positions.

6.5. *Application of chronosequence and catena studies to soils of the Front Range of Colorado*

The above soil development relations can be used to provide a time framework for the development of soils in the Front Range of Colorado. For example, a soil with a mainly cumulic A horizon denotes formation during the Holocene. Soils with a well-developed Bw horizon or a weak Bt horizon suggest formation over a period of between 10 ky and greater than 20 ky. Soils with A/brown and sandy loam Bt/Cox profiles suggest soil development of at least 50 ky and perhaps as long as 150 ky. Finally, soils with Bt horizons that are red (2.5YR) and have sandy clay loam texture, or a texture class with even more clay, denote formation over several 100 ky. Interestingly, these relations are generally true throughout the range regardless of elevation. It could be that other factors locally influence soil development, such as aspect, but consistently greater degree of soil development with stratigraphically older deposits underscores the importance of time in pedogenesis in this area.

7. Soil distribution in the Front Range of Colorado

The U.S. Department Agriculture, U.S. Forest Service (2001) has prepared soil maps of the study area at a scale of 1:24,000, following a 3rd-order soil survey (Soil Survey Division Staff, 1993). These maps show a general relation between the major soils and various elements of the landscape (Fig. 6).

Most of the mountainous terrain west of Nederland and Ward has soils with A/Bw/C and (or) R profiles in the tundra and O and (or) A/E/Bw/C and (or) R profiles in the forest. Such profiles are due either to young deposits (Pinedale age and Holocene tills and periglacial deposits) or to erosion under the present or glacial-age climate and vegetation. Rolling bedrock topography characterizes the unglaciated windswept tundra between glaciated valleys. Burns and Tonkin (1982) noted that soils on this undulating topography form a catena. The key to understanding these soils is wind redistribution of snow and dust (referred to as mixed loess when it is incorporated into the underlying soil). Both of them are minimal on the topographic highs and increase in thickness in the lee of the highs. Hence, soils on the highs are mainly thin and either lack or have a surface layer of mixed loess. Greater soil moisture downslope in the lee positions results in progressively better developed and thicker soils, as well as a mixed loess surface layer. At the base of the slope, the soils show signs of poor drainage (O/Bg profiles) and the thickest mixed loess, transported from upslope chiefly during snowmelt.

Fir-spruce tree islands are a common feature in the tundra, just above tree line. They migrate downwind at a rate about 1–2 m/0.1 ky (Benedict, 1984). Holtmeier and Broll (1992) noted that the islands trap both windblown snow and fine-grained eolian material, resulting in underlying soils that are relatively leached A/Bw/C profiles and have a fine-grained surface layer. Burns has noted that the B-horizon hue under these tree islands is 7.5YR versus 10YR in the surrounding tundra. Only where the tree islands move slow enough is there sufficient time for E horizons to form (Benedict, 2000).

Many of the soils on the erosion surface are O and (or) A/Bt/C and (or) R profiles. These soils are extensive on wide tracts of the erosion surface. Eastward, the erosion surface consists of accordant ridges, and where the ridges are narrow the soils are A/Bw/C

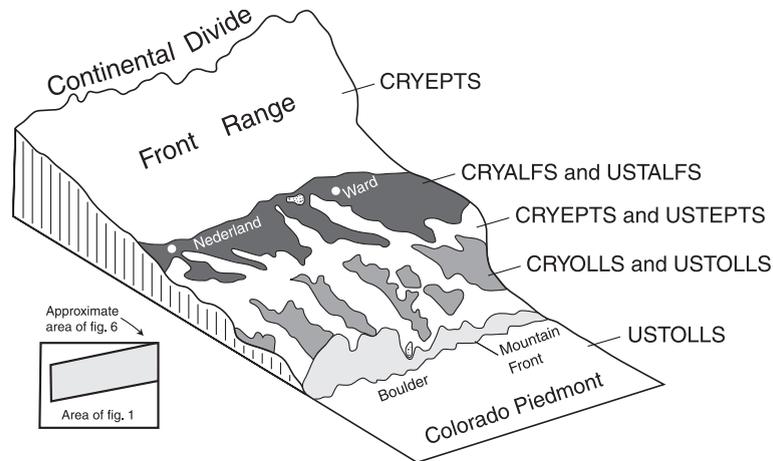


Fig. 6. Schematic perspective diagram showing relations between soils and landscape in the Front Range of Colorado and adjacent Colorado Piedmont between Boulder and the Continental Divide. Cryolls and Ustolls shown on S-facing slopes, but Cryalfs and Ustalfs on adjacent N-facing slopes cannot be shown because of the orientation of the diagram. Cryepts commonly form in the steep terrain west of the erosion surface; they have A/Bw/C and (or) R profiles (tundra) as well as O and (or) A/E/Bw/C and (or) R (forest) profiles. Cryalfs and Ustalfs commonly form on the erosion surface east of Ward and Nederland. They have O and (or) A/E/Bt/C and (or) R profiles. Dotted patterns in two small areas near Ward and Boulder are Cryalfs that have clayey, red (2.5YR hue) Bt horizons. Cryolls and Ustolls commonly form on S-facing slopes in the canyons incised into the erosion surface; they have A/Ej/Bw/C and (or) R as well as A/Bw/C and (or) R profiles. Ustolls commonly form in the plains; they have A/Bw/Bk and A/Bt/K profiles. Gray pattern along the mountain front indicates a large area of bedrock that is locally mantled by surficial deposits and their associated soils. Soil distribution, classification, and horizon designations are modified from maps (1:24,000 scale) and profile descriptions by the U.S. Department Agriculture, U.S. Forest Service (2001, and written communication, 1999, respectively).

and (or) R profiles. Interestingly, these well-developed soils with Bt horizons remain well expressed adjacent to areas formerly covered by Pinedale ice. We interpret this to mean that periglacial processes were not of sufficient intensity or duration to erode these soils. If this is correct, then these parts of the erosion surface have been stable for at least 100 ky. On the erosion surface near Ward (Fig. 6), there is a small area of soil with a morphology similar to the above, except that the Bt has a 2.5YR hue and a sandy clay texture. Comparing this soil with those in the plains suggests several 100 ky of landscape stability to form such a soil.

Soils on the N-facing versus S-facing valley sides (U.S. Department Agriculture, U.S. Forest Service, 2001) provide an opportunity to compare the influence of aspect on soil development (Fig. 7). In the tundra, as well as in the subalpine forest, soil maps show little difference in soil morphology between N- and S-facing slopes. Most of the above soils are Cryepts with a similar horizon sequence. Apparently, the combination of relatively high precipitation and

low temperature negates the effect of aspect. From the western edge of the erosion surface to the mountain front, however, N-facing soils are mainly O and (or) A/E/Bt/Bw/C and (or) R profiles. In contrast, S-facing soils have A/Ej/Bw/C and (or) R profiles and the A horizons of these soils are thicker than the O and (or) A horizons of the N-facing soils. These profile contrasts result in Cryalfs on the N-facing slopes and Cryolls on the S-facing slopes; if temperatures are frigid at lower elevations, however, the soils are classified as Ustalfs and Ustolls, respectively. This contrast in soil-profile development could either be a function of age (N-facing slope deposits are more stable and older) or of process (Bt horizons form faster on N-facing slopes due chiefly to greater effective soil moisture).

Reconnaissance work by bicycle in many road cuts along main and mining roads in the mountains indicates that grus development shows a strong relation with topographic setting and geological history. Clayton et al. (1979) have developed a seven-class classification of granite weathering. Class 1 is unweathered

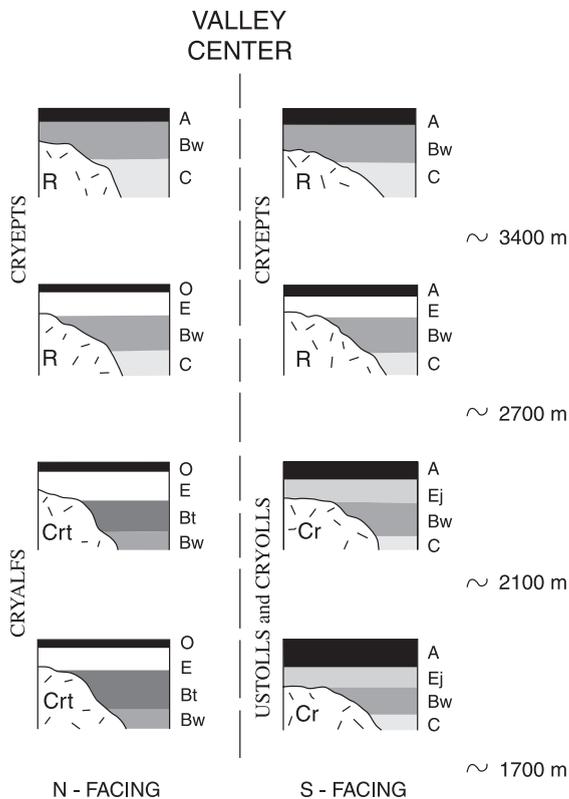


Fig. 7. Generalized diagram showing soil profiles on N-facing versus S-facing slopes in the canyons near Boulder. Each profile is about 1 m thick. We estimate that S-facing slopes have the cryic–frigid soil–temperature–regime boundary within the upper montane vegetation zone. Some N-facing slopes can have a cryic soil–temperature regime to the mountain front; if warmer at lower elevations, however, the soil–temperature regime is frigid and the soils are Ustalfs. Modified from maps and profile descriptions by the U.S. Department Agriculture, U.S. Forest Service (2001, and written communication, 1999).

rock; class 2 is oxidized rock with angular joint–plane junctions. Classes 3–6 are subdivided on the distinctness and rounding of the joint plane junctions (gone by class 5, and this is approximately where *grus* appears in the weathering sequence) and the ease with which rock fragments disaggregate (easily disaggregates in class 6). Class 7 exhibits rock fabric, but chemical weathering is advanced enough to form clay. The first task is to make sure that hydrothermal alteration is not confused with surface weathering. The landscape west of the erosion surface is generally class 1, especially the part that was covered by Pinedale glaciers. Class 2 weathering is common through-

out the rest of the range, suggesting either moderate erosion or a slow rate of weathering. In contrast, just west of the contact between the sedimentary rocks and the igneous–metamorphic complex is a narrow linear band of rocks with class 4–6 weathering. This could be due to more intense weathering at the eastern margin of the range, or weathering association with the paleosol formed in granodiorite beneath the lowest sedimentary rocks (Fountain Formation of Permian and Pennsylvanian age), thoroughly studied by Wahlstrom (1948). Our interpretation of the paleosol is that it is mainly a thick section of *grus* (class 6 maximum) (Birkeland et al., 1996). We suggest that the linear band of class 4–6 *grus* is either a lateral expression of Wahlstrom’s paleosol (*grus*), or it is some combination of pre-Fountain weathering of the granodiorite enhanced by weathering during the Late Cenozoic. Other areas of thick class 4–6 *grus* have escaped erosion over the long-term for a variety of reasons, one being the low rate of local steam incision.

The higher classes of granite weathering indicate landscapes that were not rapidly eroded over long periods of time. We do not know the rate of *grus* formation, but we can make an estimate by considering the condition of boulders in tills. Those in tills of Pinedale age are generally unweathered, but some in tills of Bull Lake age are sufficiently weathered to be class 4–6. Assuming this, *grus* formation can also take place in soil formed from rock and that most soils are a minimum of 1 m thick, a 1-m thick layer of *grus* formed from granitic or gneissic bedrock probably takes a minimum of about 100 ky to form.

8. Some applications of soils of the Front Range of Colorado

Soils can be used to estimate incision rates of the canyons that characterize the Front Range of Colorado. One can use the ages of the fluvial terrace deposits at the mouths of the canyons—many estimated by their associated soils—to estimate incision rates, and then compare these soils with those on canyon side slopes. Using the former, Dethier et al. (2000) calculated an incision rate of 0.04 m/ky in the plains at the mouth of Boulder Canyon. Schildgen (2000) and Schildgen and Dethier (2000) used soils to help guide a radiocarbon and cosmogenic isotope

dating study within Boulder Canyon; they identified deposits of Holocene, Pinedale, Bull Lake, and pre-Bull Lake ages. At a major knickpoint within the canyon, they calculate an incision rate of 0.15 m/ky. The contrast between this higher rate and the much lower rate determined in the plains might be due in part to the upstream migration of the knickpoint or to the durability of the bedrock at or near the knickpoint. Most soils on side slopes in Boulder Canyon seem to be fairly young, less than 20 ky. This seems fitting as the side slopes are steep, cliffs are common, and of the three streams here compared, Boulder Creek has the highest discharge and was the most extensively glaciated in its headwaters. The next major canyon to the north, Left Hand, has an incision rate in the plains near the mountain front of 0.05–0.1 m/ky (range in values is due to which fluvial deposit is used as a datum). In Left Hand Canyon, the headwaters were not extensively glaciated, the canyon side slopes are more gentle than those in Boulder Canyon, and soils with Bt horizons on side slopes are more common. A major canyon south of Boulder Canyon is the unglaciated Coal Creek Canyon, where incision in the plains at the mountain front is 0.006 m/ky. Soils on the valley sides near the canyon mouth commonly have red, clay-rich Bt horizons that suggest they formed over several 100 ky (Birkeland et al., 1996). Thus, soils on side slopes of the canyons correspond with incision rates. Coal Creek has the lowest incision rate and the oldest soils on side slopes. Boulder Creek has a high incision rate and the youngest soils on side slopes. The differences in the development of soils on side slopes in Boulder Canyon and Left Hand Canyon could be related to the higher discharge, more extensive glacier activity, and knickpoint migration in the former.

Veblen and Lorenz (1991) have documented the great change in vegetation in the Front Range of Colorado during the last century. Many of the changes are associated with mining, and the logging and burning that accompanied the mining. Many slopes were extensively revegetated. Reconnaissance study of road cuts along many mining roads in the mountains via bicycle reveals neither widespread extensive erosion (enough to remove the steady-state A horizons that take several thousand years to form) nor deposition (buried soils) in these disturbed areas. These observations suggest that the mountain slopes outside

of the heavily mined sites did not respond drastically to perturbations caused by human activities.

Quaternary climate change can be deciphered in some soils. Shroba and Birkeland (1983) note the presence of vermiculite and a high degree of illite (mica) weathering in soils now 100 m above tree line. Because vermiculite is a forest indicator (Netoff, 1977; Shroba and Birkeland, 1983), these data suggest a tree line higher than present sometime during the Holocene. Organo-cutans are dark brown organic stains that form on the undersides of stones in the lower part of the B horizon and in the C horizon of alpine soils that lack excessive snow cover (Burns, 1980; Benedict, 2000, Appendix B). Burns and Davenport (1988) observe these stains in forested soils at elevations as low as 2735 m, suggesting that they formed in alpine soils during glacial-age lowering of upper tree line of greater than 700 m. This interpretation is consistent with pollen data that suggest 500–800 m of tree line lowering during the Pinedale glaciation (Legg and Baker, 1980; Madole, 1986). Strongly developed E horizons that persist to the mountain front might partly be a legacy of glacial climates, and the intact profiles suggest little tree throw. Finally, Btk horizons are common in the plains; this mix of carbonate depletion and accumulation in the same horizon might reflect leaching during glacial climate and accumulation during interglacial climate, respectively.

The rate of carbon accumulation and its storage in soils are important issues in current biogeochemical cycling studies. These trends are best studied by soil chronosequence studies. Bockheim et al. (1998) have taken data from our studies in the Front Range of Colorado, the Wind River Range of Wyoming, and the Southern Alps of New Zealand to make comparative accumulation curves for alpine environments. The New Zealand soils accumulate carbon faster and reach higher levels of carbon content, and those of the Front Range of Colorado rank higher on both accounts than those of the Wind River Range. We need more of these kinds of data for many other environments, such as those for the forests of the Front Range of Colorado.

Soil-profile development can be used to estimate long-term (20–100 ky) rates of lowering of the landscape (denudation). A/Bt/C profiles, such as those associated with the erosion surface, are best

for placing broad limits on rates of denudation. These soils take about 100 ky to form and typically the base of the Bt horizon is close to 1-m depth. Therefore, to preserve such a profile, denudation had to be much less than 1 m/100 ky (0.01 m/ky), and perhaps no more than 0.1 m/100 ky (0.001 m/ky). Those small areas of soils with red, clay-rich Bt horizons would have an even lower rate of denudation. Comparing the latter denudation rate for the erosion surface (0.001 m/ky) with the incision rate of Boulder Canyon mentioned earlier (0.04 m/ky) suggests that relief in Boulder Canyon is increasing. The mountains west of the erosion surface, outside of the areas covered by Pinedale glaciers, are characterized by O and (or) A/Bw/C and (or) R soil profiles. One possible denudation scenario is that these soils formed in the last 10–20 ky following sufficiently rapid denudation during the Pinedale glaciation to have removed the pre-existing soils. Assuming 1-m-deep profiles, their preservation requires a denudation rate much less than 0.05–0.1 m/ky, perhaps as low as 0.005–0.01 m/ky. This latter denudation rate is greater than that estimated for areas characterized by soils with A/Bt/C profiles because Bw horizons form more rapidly than Bt horizons. The latter range agrees with that calculated by Caine (1984; personal communication in Thorne and Loewenherz, 1987) for the tundra-covered Green Lakes Valley, just south of Niwot Ridge.

Niwot Ridge is a broad, gently rolling ridge above tree line, with a maximum elevation of about 3700 m. It is characterized by A/Bw/C soil profiles (Burns and Tonkin, 1982). Solifluction and frost creep have been active in moving surficial materials downslope during the Holocene (Benedict, 1970). Bovis and Thorn (1981) measured contemporary erosion on Niwot Ridge and calculated denudation rates. If we extrapolate their rates over a longer time frame, the rate for the tundra meadow would be 0.01 m/ky (1 m/100 ky), and that for the dry meadow would be 0.1 m/ky (10 m/100 ky). These high values make us suspect that these measured rates should not be extrapolated so far back in time. The previous authors as well as Caine (1974) used Benedict's (1970) surface-material transportation rates, most taken at sites that were quite active, to calculate a denudation rate of 0.01 m/ky (1 m/100 ky). All of these rates have problems associated with them, and one important thing is the

accumulation of wind-blown fines, which produce a result opposite to that of denudation. In any case, over long periods of time, the lower of the two rates above would be compatible with the A/Bw/C soil profiles on Niwot Ridge, but the higher rate could not have been sustained for even 10 ky and allow preservation of the soils.

The above rates of denudation for the mountains west of the erosion surface (0.005–0.01 m/ky) and for Niwot Ridge (0.01 m/ky) seem reasonable when compared with other cosmogenic radionuclide erosion rates in the nearby Front Range of Colorado. Small et al. (1997) calculate rates for tors and a large boulder of 0.007–0.008 m/ky. These dated features are on summit surfaces above treeline, at 3,575–3,734 m. The erosion rates for tors should be considered minimal because they are low, isolated features on low-relief terrain. The above rates are lower than those of Dethier et al. (2002) who determined 0.018–0.030 m/ky for sediment removed from small (<50 km²), non-glaciated catchment basins on granitic and gneissic bedrock in the northern Front Range of Colorado and the Laramie and Medicine Bow Ranges of southern Wyoming.

9. Summary

Soils reflect the geomorphic setting of the Front Range of Colorado. The Front Range is an old range, with canyons cut during the last 5 my. Glaciation affected the western quarter or third of the range east of the Continental Divide. MAP doubles from the plains to the divide and MAT decreases 14 °C over the same distance; these environmental differences result in contrasts in soil profiles. Soil chronosequence studies help identify surfaces and deposits that have been stable during the Holocene, for about 20, 100, and several 100 ky in the mountains, and for as long as about 2 my in the plains. Compared to a tectonically active range, such as the Southern Alps of New Zealand, soils in the Front Range of Colorado on predominately transport-limited slopes indicate that the latter is geomorphically quite stable, and most similar to the drier parts of the Southern Alps. Future work could concentrate on how soil-development patterns relate to geomorphic activity with elevation in the Front Range of Colorado (Caine, 1984). Appli-

cations of soils include (1) helping to estimate stream incision rates in the canyons; (2) linking the latter to soil patterns on canyon side slopes following the model that *Tonkin and Basher (1990)* developed in the Southern Alps of New Zealand; (3) assessing landscape stability following disruption accompanying mining; (4) assessing the effects of Quaternary paleoclimate on the landscape as well as on soil development; and (5) estimating long-term denudation rates.

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References

- Barry, R.G., 1973. A climatological transect on the east slope of the Front Range, Colorado. *Arct. Alp. Res.* 5, 89–110.
- Benedict, J.B., 1970. Downslope soil movement in a Colorado alpine region: rates, processes, and climatic significance. *Arct. Alp. Res.* 2, 165–226.
- Benedict, J.B., 1984. Rates of tree-island migration, Colorado Rocky Mountains, USA. *Ecology* 27, 820–823.
- Benedict, J.B., 1985. Arapaho Pass. Glacial geology and archeology at the crest of the Colorado Front Range. Center for Mountain Archeology, Research Report, 3, 197 pp.
- Benedict, J.B., 2000. Game drives of the Devil's Thumb Pass Area. In: Cassells, E.S. (Ed.), *This Land of Shining Mountains*. Center for Mountain Archeology, Research Report, 8, 18–94.
- Berry, M.B., 1987. Morphological and chemical characteristics of soil catenas on Pinedale and Bull Lake moraine slopes in the Salmon River Mountains, Idaho. *Quat. Res.* 28, 210–225.
- Birkeland, P.W., 1999. *Soils and Geomorphology*. Oxford Univ. Press, New York. 430 pp.
- Birkeland, P.W., Burke, R.M., Shroba, R.R., 1987. Holocene alpine soils in gneissic deposits, Colorado Front Range. *U.S. Geol. Surv. Bull.* 1590. 21 pp.
- Birkeland, P.W., Miller, D.C., Patterson, P.E., Price, A.B., Shroba, R.R., 1996. Soil-geomorphic relationships near Rocky Flats, Boulder and Golden, with a stop at the pre-Fountain Formation paleosol of Wahlstrom (1948). *Colo. Geol. Surv., Spec. Publ. (CD-ROM)* 44. 13 pp.
- Bockheim, J.G., Birkeland, P.W., Bland, W.L., 1998. Carbon storage and accumulation rates in alpine soils: evidence from Holocene chronosequences. In: Lal, R., Kimble, J.M., Stewart, B.A. (Eds.), *Global Climate Change and Cold Regions Ecosystems*. Lewis Publishers, Boca Raton, pp. 185–196.
- Bovis, M.J., Thorn, C.E., 1981. Soil loss variation within a Colorado alpine area. *Earth Surf. Processes Landf.* 6, 151–163.
- Braddock, W.A., Cole, J.C., 1990. Geologic map of Rocky Mountain National Park and vicinity, Colorado. *U.S. Geol. Surv. Misc. Investigations Series Map I—1973*.
- Bradley, W.C., 1987. Erosion surfaces of the Colorado Front Range: a review. In: Graf, W.L. (Ed.), *Geomorphic Systems of North America*. Geol. Soc. Amer., Centennial Spec., vol. 2, pp. 215–220.
- Burns, S.F. 1980. Alpine soil distribution and development, Colorado Front Range. PhD Dissertation, Univ. Colorado, Boulder. 360 pp.
- Burns, S.F., Davenport, R.E., 1988. Using organo-cutans in subalpine soils as indicators of a past lower treeline. *Amer. Quaternary Assoc., 10th Biennial Meeting, Program and Abstracts*, p. 57.
- Burns, S.F., Tonkin, P.J., 1982. Soil geomorphic models and spatial distribution and development of alpine soils. In: Thorn, C.E. (Ed.), *Space and Time in Geomorphology*. Allen and Unwin, London, pp. 25–43.
- Caine, N., 1974. The geomorphic processes of the alpine environment. In: Ives, J.D., Barry, R.G. (Eds.), *Arctic and Alpine Environments*. Methuen, London, pp. 721–748.
- Caine, N., 1984. Elevational contrasts in contemporary geomorphic activity in the Colorado Front Range. *Stud. Geomorphol. Carpatho-Balc.* 18, 5–31.
- Clayton, J.L., Megahan, W.F., Hampton, D., 1979. Soil and bedrock properties: weathering and alteration products and processes in the Idaho batholith. *USDA For. Serv. Res. Pap. INT-237*. 35 pp.
- Davis, P.T., Birkeland, P.W., Caine, N., Rodbell, D.T., 1992. New radiocarbon ages from cirques in Colorado Front Range. *Geol. Soc. Amer., Abstr. Programs* 24 (7), A347.
- Dethier, D.P., Schildgen, T.F., Bierman, P., Caffee, M., 2000. The cosmogenic isotope record of late Pleistocene incision, Boulder Canyon, Colorado. *Geol. Soc. Amer., Abstr. Programs* 32 (7), A473.
- Dethier, D.P., Ouimet, W., Bierman, P., Finkel, R.C., 2002. Long-term erosion rates derived from ¹⁰Be in sediment from small catchments, Northern Front Range and Southern Wyoming. *Geol. Soc. Amer., Abstr. Programs* 34 (6).
- Holtmeier, F., Broll, G., 1992. The influence of tree islands and microtopography on pedoecological conditions in the forest–alpine tundra ecotone on Niwot Ridge, Colorado Front Range, USA. *Arct. Alp. Res.* 24, 216–228.
- Jenny, H., 1980. *The Soil Resource—Origin and Behavior*. Springer, New York. 377 pp.

- Lanphere, M.A., Champion, D.E., Christiansen, R.L., Izett, G.A., Obradovich, J.D., 2002. Revised ages for tuffs of the Yellowstone Plateau volcanic field: assignment of the Huckleberry Ridge Tuff to a new geomagnetic polarity event. *Geol. Soc. Amer. Bull.* 114, 559–568.
- Legg, T.E., Baker, R.G., 1980. Palynology of Pinedale sediments, Devlins Park, Boulder County, Colorado. *Arct. Alp. Res.* 12, 319–333.
- Lovering, T.S., Goddard, E.N., 1950. Geology and ore deposits of the Front Range, Colorado. U.S. Geol. Surv. Prof. Pap. 223. 319 pp.
- Machette, M.N., 1975. The Quaternary geology of the Lafayette Quadrangle, Colorado. Master's thesis, Univ. Colorado, Boulder. 105 pp.
- Machette, M.N., 1977. Geologic map of the Lafayette Quadrangle, Adams, Boulder, and Jefferson Counties, Colorado. U.S. Geol. Surv. Geologic Quadrangle Map GQ-1392.
- Machette, M.N., 1985. Calcic soils of the southwestern United States. *Geol. Soc. Amer. Spec. Pap.* 203, 1–21.
- Machette, M.N., Birkeland, P.W., Markos, G., Guccione, M.J., 1976. Soil development in Quaternary deposits in the Golden-Boulder portion of the Colorado Piedmont. *Prof. Contrib. Colo. Sch. Mines* (8), 217–259.
- Madole, R.F., 1969. Pinedale and Bull Lake glaciations in upper St. Vrain drainage basin, Boulder County, Colorado. *Arct. Alp. Res.* 1, 279–287.
- Madole, R.F., 1986. Lake Devlin and Pinedale glacial history, Front Range, Colorado. *Quat. Res.* 25, 43–54.
- Madole, R.F., 1991. Colorado Piedmont section. In: Morrison, R.B. (Ed.), *Quaternary Nonglacial Geology: Conterminous United States*. *Geol. Soc. Amer., The Geology of North America*, vol. K-2, pp. 456–462.
- Madole, R.F., Shroba, R.R., 1979. Till sequence and soil development in the North St. Vrain drainage basin, east slope, Front Range, Colorado. In: Ethridge, F.G. (Ed.), *Field Guide, Northern Front Range and Northwestern Denver Basin, Colorado*. Dept. Earth Resources, Colorado State University, Ft. Collins, pp. 123–178.
- Madole, R.F., VanSistine, D.P., Michael, J.A., 1998. Pleistocene glaciation in the upper Platte River drainage basin, Colorado. U.S. Geol. Surv. Geol. Investigations Series Map I—2644.
- Mahaney, W.C., 1974. Soil stratigraphy and genesis of neoglacial deposits in the Arapaho and Henderson cirques, central Colorado Front Range. In: Mahaney, W.C. (Ed.), *Quaternary Environments*. Atkinson College/York University Monograph No. 5, Toronto, Canada, 197–240.
- McMillan, M.E., 1990. Soil development on a subalpine Pinedale moraine and erosion ten years after a burn, Rocky Mountain National Park, Colorado. Master's thesis, Univ. of Colorado, Boulder. 91 pp.
- Muhs, D.R., Benedict, J.B., Evans, J., 1992. Sources of probable eolian sediments on late Quaternary alpine moraines, Colorado Front Range—evidence from trace element geochemistry. *Amer. Quaternary Assoc., 12th Biennial Meeting, Program and Abstracts*, p. 73.
- Muhs, D.R., Aleinikoff, J.N., Stafford Jr., T.W., Kihl, R., Been, J., Mahan, S.A., Cowherd, S., 1999. Late Quaternary loess in northeastern Colorado: part I—age and paleoclimatic significance. *Geol. Soc. Amer. Bull.* 111, 1861–1875.
- Muhs, D.R., Simmons, K.R., Steinke, B., 2002. Timing and warmth of the last interglacial period: new U-series evidence from Hawaii and Bermuda and a new fossil compilation for North America. *Quat. Sci. Rev.* 21, 1355–1383.
- Nelson, A.R., Shroba, R.R., 1998. Soil relative dating of moraine and outwash–terrace sequences in the northern part of the upper Arkansas Valley, central Colorado, U.S.A. *Arct. Alp. Res.* 30, 349–361.
- Netoff, D.I., 1997. Soil clay mineralogy of Quaternary deposits in two Front Range–Piedmont transects, Colorado. PhD dissertation, Univ. Colorado, Boulder. 169 pp.
- Reheis, M.C., 1980. Loess sources and loessial soil changes in a downwind transect, Boulder–Lafayette, Colorado. *Mt. Geol.* 17, 7–12.
- Richmond, G.M., 1960. Glaciation of the east slope of Rocky Mountain National Park, Colorado. *Geol. Soc. Amer. Bull.* 71, 1371–1382.
- Richmond, G.M., 1962. Quaternary Stratigraphy of the La Sal Mountains, Utah. U.S. Geol. Surv. Prof. Pap. 324. 135 pp.
- Schildgen, T.F., 2000. Fire and Ice: The Geomorphic History of Middle Boulder Creek as Determined by Isotopic Dating Techniques, Colorado Front Range. Honors thesis, Williams College, Williamstown, MA. 103 pp.
- Schildgen, T.F., Dethier, D.P., 2000. Fire and ice: using isotopic dating techniques to interpret the geomorphic history of Middle Boulder Creek, Colorado. *Geol. Soc. Amer., Abstr. Programs* 32 (7), A-18.
- Scott, G.R., Taylor, R.B., 1986. Map showing late Eocene erosion surface, Oligocene–Miocene paleovalleys, and Tertiary deposits in the Pueblo, Denver, and Greeley 1 × 2 quadrangles, Colorado. U.S. Geol. Surv. Misc. Investigation Series Map I—1626.
- Shroba, R.R., Birkeland, P.W., 1983. Trends in late-Quaternary soil development in the Rocky Mountains and Sierra Nevada of the western United States. In: Porter, S.C. (Ed.), *Late Quaternary Environments of the United States. The Late Pleistocene*, vol. 1. Univ. Minnesota Press, Minneapolis, pp. 145–156.
- Shroba, R.R., Carrara, P.E., 1996. Surficial geologic map of the Rocky Flats Environmental Technology Site and vicinity, Jefferson and Boulder Counties, Colorado. U.S. Geol. Surv. Misc. Investigations Series Map I—2526.
- Small, E.E., Anderson, R.S., Repka, J.L., Finkel, R., 1997. Erosion rates of alpine bedrock summit surfaces deduced from in situ ¹⁰Be and ²⁶Al. *Earth and Planet. Sci. Lett.* 150, 413–425.
- Soil Classification Working Group, 1998. *The Canadian System of Soil Classification*, 3rd ed. National Research Council Research Press, Ottawa Publ. 1646. 187 pp.
- Soil Survey Division Staff, 1993. *Soil Survey Manual*. U.S. Dept. Agriculture Handbook, no. 18. 437 pp.
- Soil Survey Staff, 1999. *Soil Taxonomy*, 2nd ed. U.S. Dept. Agriculture Handbook, no. 436. 869 pp.
- Steven, T.A., Evanoff, E., Yuhas, R.H., 1997. Middle and late Cenozoic tectonic and geomorphic development of the Front Range of Colorado. In: Bolyard, D.W., Sonnenberg, S.A. (Eds.), *Geologic History of the Colorado Front Range*. Rocky

- Mountain Assoc. Geologists Guidebook, Field Trip no. 7, 115–124.
- Thorne, C.E., Loewenherz, D.S., 1987. Alpine mass wasting in the Indian Peaks area, Front Range, Colorado. In: Graf, W.L. (Ed.), *Geomorphic Systems of North America*. Geol. Soc. Amer., Centennial Spec., vol. 2, pp. 238–247.
- Tonkin, P.J., Basher, L.R., 1990. Soil-stratigraphic techniques in the study of soil and landform evolution across the Southern Alps, New Zealand. *Geomorphology* 3, 547–575.
- Trimble, D.E., 1980. Cenozoic tectonic history of the Great Plains contrasted with that of the Southern Rocky Mountains: a synthesis. *Mt. Geol.* 17, 59–69.
- Tweto, O., 1979. Geologic map of Colorado. U.S. Geol. Surv.
- U.S. Department Agriculture, Soil Conservation Service, 1975. General Soil Map—Colorado, Portland, Oregon.
- U.S. Department Agriculture, U.S. Forest Service, 2001. Soil Survey of Roosevelt–Arapahoe National Forest, Colorado, Interim Version [unpublished]. Forest Supervisor's Office, U.S. Forest Service, Ft. Collins, CO.
- Veblen, T.T., Lorenz, D.C., 1991. *The Colorado Front Range, A Century of Ecological Change*. Univ. Utah Press, Salt Lake City. 186 pp.
- Wahlstrom, E.E., 1948. Pre-Fountain and recent weathering on Flagstaff Mountain near Boulder, Colorado. *Geol. Soc. Amer. Bull.* 59, 1173–1189.