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Soil Development Parameters in the Absence of a Chronosequence in a Glaciated Basin of the White Mountains, California–Nevada

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Detailed mapping and provisional numerical age determinations of glacial deposits in the South Chiatovich Creek Basin of the White Mountains provide an opportunity to evaluate the ability of conventional soil parameters to discriminate first- and second-order glacial events. Sampling and analytical procedures were designed to minimize variation in climate and lithology. When lithology and climate are similar among sites, age trends are more pronounced in both field and chemical soil properties. Profile development indices (PDIs), adjusted by removing melanization and pH, systematically increase with greater soil age, and discriminate first-order, but not second-order, glacial events. The best-fit curve for adjusted PDI data assumes an exponential form and suggests that the rate of soil formation in this region decreases over time, similar to the rate of weathering-rind development. Variation in eolian influx and surface erosion, which are dominant processes affecting soils of the basin, cause major uncertainties in establishing soil age and, hence, soil-development rates. Even on the youngest glacial deposits, soil age is probably significantly less than deposit age due to these geomorphic processes. Soil and weathering parameters imply that these field techniques can be inexpensively employed to define relative chronologies and to assess surface degradation and its impact on surface exposure ages. Results from this study indicate that site-selection strategy for establishing glacial chronologies should be reevaluated. Working with stable residual bedrock surfaces and associated low-relief outwash fans and terraces may prove more productive than focusing on relatively unstable moraine surfaces in tectonically active mountain systems. ©1993 University of Washington.

INTRODUCTION

Pedologic data have been used successfully for relative dating of Quaternary deposits in a wide range of geomorphic and environmental settings (e.g., Harden and Taylor, 1983; McFadden and Weldon, 1987; Birkeland and Burke, 1988). Such studies are based on the development of a soil chronosequence in which soils vary with age of the geomorphic surface, but are otherwise formed in similar settings of climate, vegetation, relief, and parent material (Jenny, 1941). Chronosequences are especially difficult to establish in tectonically active and glaciated mountain settings, as successive glacial deposits are often spatially separated from one another over an altitudinal gradient due to fluctuating glacier equilibrium-line altitudes (ELAs). Climate, and often vegetation, are not constant in such instances, as both precipitation and temperature usually vary with altitude. Chronosequences may also be complicated by lithologic variation due to multiple bedrock sources, influx of eolian dust, and differential erosion (McFadden and Weldon, 1987; Birkeland and Burke, 1988).

An important question is whether soil development trends can be used to discriminate first- and second-order glacial events (Porter, 1971) in the absence of a chronosequence. To address this question, we have used conventional soil parameters on a sequence of glacial deposits in the Chiatovich Creek basin, White Mountains, California–Nevada (Fig. 1). Climate and, to a lesser extent, lithology vary along an altitudinal gradient. Glacial deposits were mapped and described by Swanson *et al.* (in press) as part of an ongoing project on the glacial and environmental history of the range. The detailed chronology and regional correlation of these glacial deposits are also discussed in that paper.

Our primary objective here is to establish a rate curve for soil development in the White Mountains, knowing that variables such as climate, influx of eolian dust, and the rate of surface denudation have varied with time. Establishing such a rate curve provides a basis for making provisional age estimates for undated geologic deposits within the region, such as alluvial-fan surfaces and outwash terraces. Intervalley correlation of deposits may also be possible using such a curve, providing that non-

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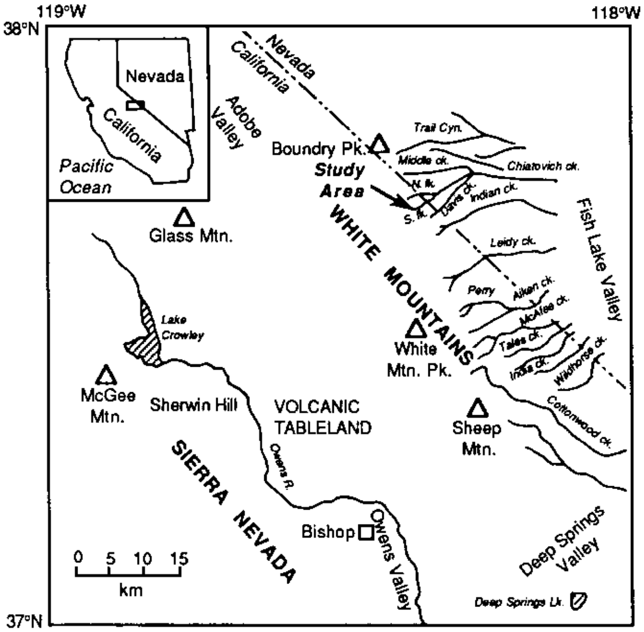

FIG. 1. Map showing location of the White Mountains and Sierra Nevada. Chiatovich Creek drainage represents one of 15 northeastern drainages of the White Mountains that were glaciated repeatedly during the Quaternary Period.

temporal factors are held relatively constant between valleys. Furthermore, such data provide important insights about the amount, and possibly the rate, of surface lowering in regions where denudation processes have modified the landscape. We believe that in geologic settings where surface erosion is not adequately considered during sampling and data interpretation, the reliability of numerical age estimates based on surface exposure dating techniques remains suspect.

Study Region

The White Mountains lie 45 km east of the Sierra Nevada along the California–Nevada border (Fig. 1), and are a northwest-trending fault block that was uplifted and tilted eastward at the same time as the Sierran block (Bachman, 1978; Chase and Wallace, 1986). Chiatovich Creek basin is a glaciated valley located on the northeast flank of the White Mountains (Fig. 1). Its watershed also includes the drainages of Davis and Middle creeks; however, only the South Fork of Chiatovich Creek was mapped and sampled in this study. The study area lies in the southeastern quarter of the Boundary Peak, Nevada–California (NV–CA), and southwestern quarter of the Davis Mountain, NV–CA, 7.5-min U.S. Geological Survey topographic quadrangles.

Chronology and Regional Correlation of Glacial Deposits in Chiatovich Creek Basin

Using a multiparameter, relative-dating approach and limited radiometric data, glacial deposits have been differentiated into six separate first-order glaciations, two of which were further subdivided into measurable second-order fluctuations (Swanson *et al.*, in press). A description of the chronology and regional correlation of glacial deposits in the Chiatovich Creek basin are discussed by Swanson *et al.* (in press) and summarized in Table 1. Glacial stage names for the Chiatovich Creek chronology were retained from Elliott-Fisk (1987).

ENVIRONMENTAL FACTORS

The establishment of a soil chronosequence in the Chiatovich Creek basin is hindered by nonuniformity in climate and lithology among sampling locations; vegetation and topography are not major constraints, as sagebrush shrublands dominate the landscape. Our sampling procedures were designed to minimize variation in microclimate and lithology. Furthermore, spatial relationships were particularly important in differentiating and correlating glacial deposits.

Parent Material

Glacial deposits are locally derived from four largely granitic lithologic units (Fig. 2). Mineral analyses of the normal-phase adamellite of the upper basin indicate that mafic mineral content (mainly biotite and hornblende) is about two to five times greater than, and the quartz content nearly half that of, the leucocratic rocks of the lower basin deposits (Crowder and Ross, 1973). Plutonic rocks containing biotite have been shown to weather more rapidly than similar rocks with leucocratic compositions (Birkeland, 1984). Consequently, the rate of weathering and pedogenesis is expected to be correspondingly greater for the normal-phase adamellite rocks and soils, providing other soil-forming factors are held equal.

Climate

Temperature and precipitation at the sampling sites vary over an altitudinal range that exceeds 2000 m, with

TABLE 1

Glacial Chronology of South Chiatovich Creek Basin, White Mountains, California–Nevada

Glacial stage name	Approximate minimum and maximum age estimates (years)
Chiatovich Cirque	10,000
Late Middle Creek	14,000
Early Middle Creek	20,000
Late Perry Aiken/Early Perry Aiken	55,000–150,000[a]
Indian	220,000–328,000[a]
Dyer	611,000–2,532,000[a]

[a] Age estimates are taken from Swanson *et al.* (in press) and are based on minimum and maximum rind thickness ratio estimates. Actual ages are inferred to lie between these extremes.

average annual temperature decreasing by ~0.65°C/100-m increase in altitude and average annual precipitation increasing by ~17 mm over a similar rise in altitude (Fig. 3). We expect that some combination of precipitation and temperature represents optimum conditions for weathering, probably within the subalpine woodland zone of the transect (e.g., early Middle Creek deposits; Figs. 2 and 3).

Erosion

Long-term erosion rates in the White Mountains are estimated to range between 1 and 3 cm/1000 yr for residual bedrock surfaces (Marchand, 1971). Erosion rates on unconsolidated moraines can be very high in semiarid, tectonically active mountain ranges where the combination of sparsely vegetated surfaces and high relief is conducive to intensive stream dissection and slope retreat (Birkeland and Burke, 1988). Birkeland and Burke (1988) suggest that erosion of the uppermost soil horizons may explain inconsistencies between eastern Sierra Nevada soils data and expected age relationships of moraines.

Strong temporal relationships exist between the morphostratigraphy of glacial deposits in the Chiatovich Creek Basin and the degree of stream incision and surface erosion (Swanson *et al.*, in press). The Chiatovich Cirque and younger Middle Creek moraines still retain relatively sharp crests (slope angle >28°) exhibiting little surface erosion, with only minor stream incision through the deposits (Fig. 4). The Perry Aiken moraines are deeply dissected (>15 m) and possess relatively subdued surface morphologies (slope angle ~17–20°) (Fig. 5). The Indian, Dyer, and Chiatovich flats tills no longer retain a true matrix, but consist of residual till boulders overlying erosional bedrock surfaces (Figs. 6). As a consequence of surface denudation, these deposits yields soil ages that are considerably younger than the age of deposition.

Eolian Dust Influx

Several studies (e.g, Marchand, 1970; McFadden and Weldon, 1987) have shown that eolian dust influx is one of the most important factors in soil development on late Quaternary landforms in arid regions of the American Southwest. McFadden and Weldon (1987) indicate that eolian processes not only contribute clay, silt, and calcium carbonate to soils, but also alter iron oxide content and composition, with accumulated iron oxides derived mainly from incorporation of eolian sediments rather than by chemical alteration of the original parent material.

Although eolian dust influx has not been measured in the Chiatovich Creek Basin, inferences can be drawn from the work of Marchand (1970) and Reheis (1988). Marchand (1970) concluded that up to 30% of the very fine sand and 50% of the silt fractions were derived from eolian sources. Mineralogical investigation of lithosols formed from dolomitic substrates in the southern White Mountains indicates that local eruptions of the Mono–Inyo crater complexes are responsible for much of this "soil contamination" (Marchand, 1970).

Reheis (1988) used a network of 63 dust traps, including traps in Fish Lake Valley on the eastern side of the White Mountains, to estimate the regional composition and influx rate of aerosolic dust in southern Nevada and California. Silt and clay were found by Reheis (1988) to dominate particle-size fractions. Sites close to source regions (i.e., playas or alluvial fans) yielded samples with as much as 50% fine sand. Calcium carbonate constituted 3 to 25% of the dust, and was found to strongly controlled by proximity to potential carbonate sources.

METHODS

Swanson *et al.* (in press) differentiated first-order glacial episodes using a multifaceted approach. Preliminary grouping of deposits on the basis of topographic position and morphostratigraphic data provided an initial basis for differentiating formal glacial stages, but did not ensure that each deposit is from a separate glacial event. Rock-weathering parameters of glacial deposits that have been mapped and tentatively differentiated according to morpho- and lithostratigraphic criteria were then compared with one another in a sequential manner to differentiate measurable age trends.

To determine how substantial a change in soil development is required to separate first-order glacial events, attention is paid to the topographic and lithologic relationships of the deposits within a particular area. If two moraines inferred to represent two different glacial stages are spatially proximal, such that their lithologic composition and climatic environments are similar, then a difference in soil development is expected. However, if the moraines are spatially separated, such that the lithologic composition of the till and/or climatic conditions are significantly different at the two sites, it may not be possible to separate the temporal effects on soil development from the nontemporal factors.

Soils data from the inferred youngest deposit (i.e., Chiatovich Cirque) were compared to those from the adjacent set of moraines downbasin (i.e., Late Middle Creek) using all of the measured parameters. Because of the small number of representative sample sites from each respective drift unit, comparison of soils data was based largely on means and standard deviations and qualitative evaluation of parameters that are not easily quantified. Because of the presumed progressive age increase with decreasing altitude, the end moraine of one advance should be directly upbasin from the recessional deposits of an older advance, providing the older deposit was not obliterated by subsequent erosion or deposition. If the

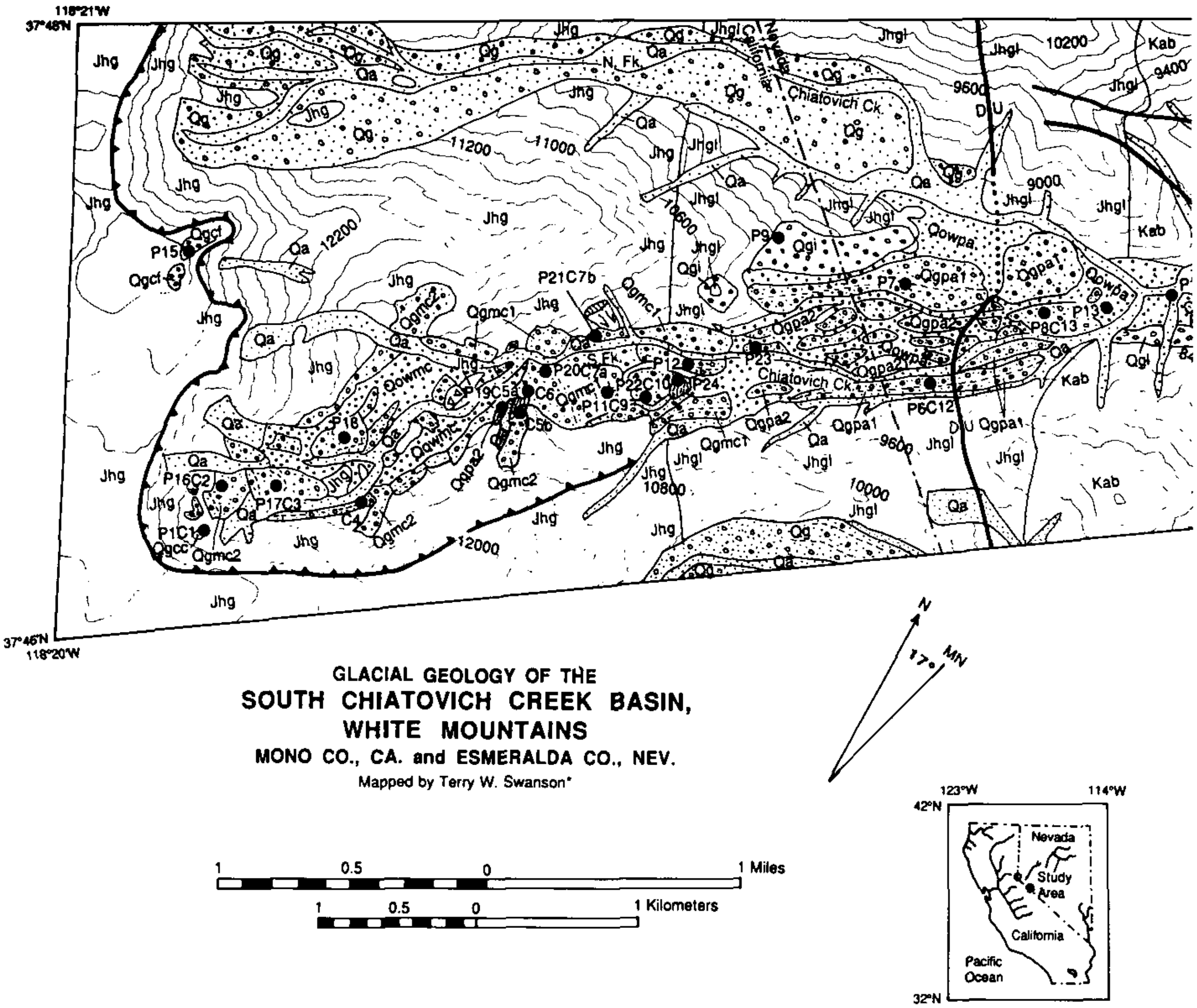

FIG. 2. Glacial geologic map of the South Chiatovich Creek Basin, White Mountains, California–Nevada. Bedrock geology in part derived from Crowder *et al.* (1972) (Benton 15-minute quadrangle, CA–NV).

time interval between the two advances was sufficiently long, soil development trends should show a significant break between sites. Abrupt changes in soil development provide a basis for differentiating first-order glaciations (Burke and Birkeland, 1979). Smaller or inconsistent breaks within the data probably indicate second-order (stadial) events within a glaciation or significant erosion of the moraine since deposition. In this report, a soil developed on a given drift is designated informally by the name of the drift (e.g., Chiatovich Cirque soil is the soil developed on Chiatovich Cirque drift, and therefore postdates deposition of the drift).

Field Analyses

Twenty-three soil profiles were excavated, sampled, and described in the field using the following procedures.

Soil pit site selection. Soil pits were dug deeply enough to expose the assumed parent material along the most-level section of moraine crests. The general morphology of the moraines and the basin did not always permit pit sites to be selected with similar aspects, but in most cases slope aspect did not vary significantly among sites.

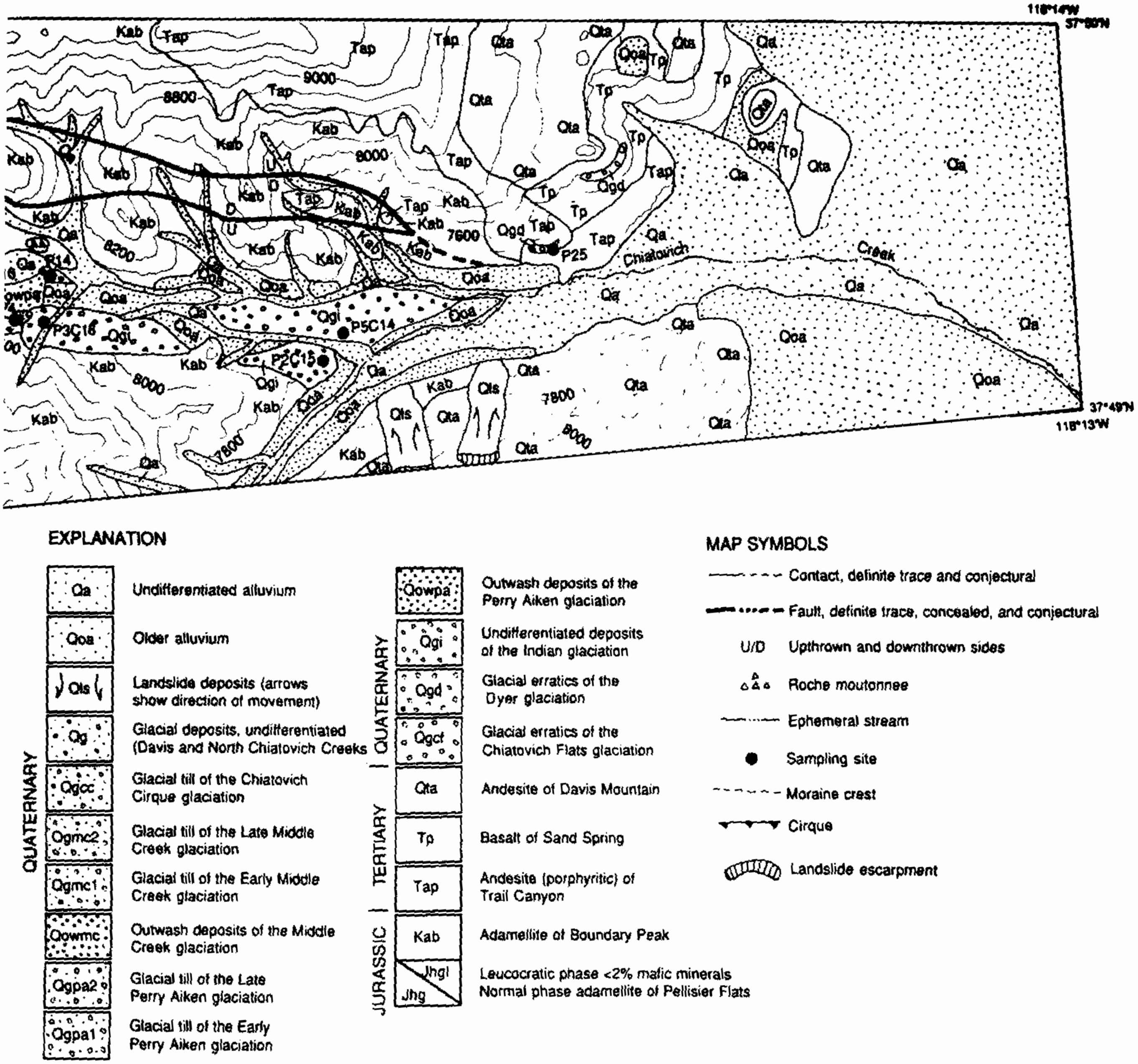

FIG. 2—*Continued*

Field properties. Soil properties were described and measured in the field using horizon nomenclature of the Soil Conservation Service (Soil Survey Staff, 1981). Soil properties measured in the field include horizonation, color, texture, consistence, structure, pH, and other pedologic features such as clay films, pores, and roots.

Field properties were quantified using a profile development index (Harden, 1982; Harden and Taylor, 1983) for soils developed in till. Soils forming on till-veneered residual bedrock surfaces were not indexed because of parent material differences.

Laboratory Analyses

Each horizon sample was air-dried and passed through a 2-mm-mesh sieve. The following analysis procedures are outlined by Singer and Janitzky (1986): particle-size distribution, including gravels (>2 mm diameter), by pipette and sieving following removal of organic matter (with H_2O_2) and iron oxides (with citrate–bicarbonate–dithionite, CBD); soil pH on 1:1 soil:water suspensions with a Corning pH meter; CBD-extractable Fe (Fed) and Al (Ald) and organic carbon by dry combustion of materials ground to pass an 80-mesh sieve. Acidic ammonium

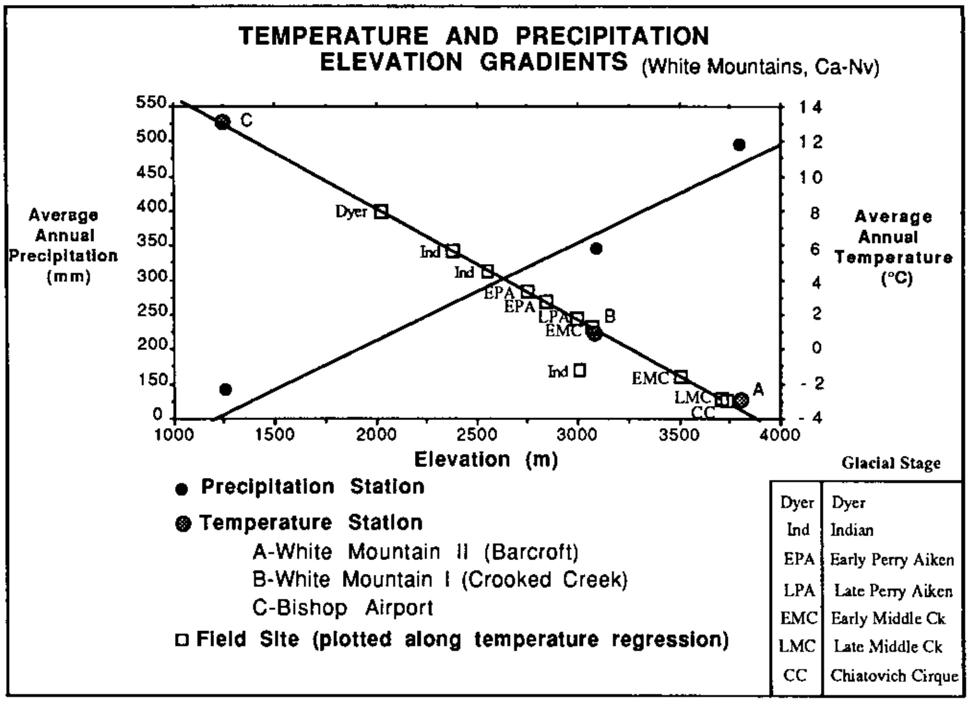

FIG. 3. Precipitation and temperature regressions as a function of elevation for the northeastern White Mountains. Field site numbers and corresponding glacial stages are plotted along the temperature regression. Regression lines are derived from climatic data from Dyer, White Mountain I (Crooked Creek Laboratory) and White Mountain II (Mount Barcroft Laboratory) climate stations (Pace *et al.*, 1974).

oxalate (McKeague and Day, 1966) was used to extract amorphous forms of Fe (Feo) and Al (Alo). Organic matter was removed (with H_2O_2) from samples prior to CBD and oxalate treatments. Concentrations of Fe and Al in extracts were measured by inductively coupled plasma and atomic absorption spectroscopy.

The overall gain of a particular Fe and Al component due to pedogenesis for the entire profile was calculated by summing the net increases of the component (weight percentage of each component in a measured horizon minus that in the assumed parent material times the horizon thickness) of all horizons above the least-oxidized horizon (McFadden and Weldon, 1987).

RESULTS

Morphologic Properties

Soils forming on Chiatovich Cirque and Middle Creek moraines consist mainly of A/C and A/CB/C profiles, with little pedogenic alteration throughout the profile. Soil depths are generally shallow, with the solum thickness rarely exceeding 20 cm. Chiatovich Cirque and Middle Creek soils show very little color difference from the parent material. Hues of 10YR are consistent throughout the profiles for the nine younger sites; variation in color value reflects variation in organic matter accumulation.

Soils forming on Perry Aiken moraines consist of profiles with incipient B horizons (AB, BC), characterizing late-stade deposits, and Bt horizons on moraines of the earlier stade. Profile depths rarely exceed 35 cm, although the solum of the the Early Perry Aiken terminus soil (site P8C13) reaches a depth of 46 cm. This increased profile depth relative to the other soils on Perry Aiken drift may be due to a "terminal effect," which Burke and Birkeland (1979) identify as relatively stronger weathering on terminal moraines than on lateral moraines. Soils formed on Perry Aiken moraines show slightly greater rubification than those on Middle Creek drift, with hues changing from 10YR to 7.5YR in the B horizons of these profiles. Such hue changes are not well expressed in the soil profiles formed on bedrock residua (sites P13 and P19C5a) or in glaciofluvial sediments (site P10). Melanization follows trends similar to those of the Middle Creek and Chiatovich Cirque soils, with lower values representing the organic-rich A horizons.

Potential age relationships of soils formed on Indian deposits are complicated, as the profiles may represent multiple depositional events, as well as soil burial (site P14). Indian profiles forming on residual bedrock surfaces possess little fine matrix (e.g., sites P2C15, P3C18, P5C14, and P9; Fig. 2). Indian soils with a fine matrix (sites P4 and P14) exhibit greater B-horizon development than soils forming on similar substrates of Perry Aiken age. These two profiles on Indian drift extent to depths >60 cm. Site P14 has three buried B horizons with a combined thickness of >80 cm. The C horizon of this pedon was not reached. The Indian soils formed on re-

FIG. 4. Small sharp-crested end moraines of Middle Creek age in the upper South Chiatovich Creek basin extend upvalley to 3680 m elevation. The terminus of the Late Middle Creek advance is represented by a bouldery moraine loop (middle distance) (site P18) consisting of subangular to angular till boulders. The photo was taken from site P17C3 looking toward the northeast.

sidual bedrock surfaces also have well-developed Bt horizons, but profile depth rarely reaches 30 cm. Hue characteristics in profiles on Indian drift follow trends similar to those on Perry Aiken deposits. However, the thickness of the rubified horizon of the till-derived Indian soils is substantially greater than those on Perry Aiken drift. Indian soils formed on residual bedrock surfaces (e.g., sites P2C15, P5C14, P9) also possess strongly rubified horizons. This was not the case for Perry Aiken soils formed on similar surfaces (sites P13 and P19C5a). In all cases, 7.5YR was the reddest hue observed in the Indian soils, whereas the assumed parent material has a hue of 10YR. Melanization trends are similar to those of the Perry Aiken and Middle Creek soils. Charcoal fragments were found in the surface horizons of P4 and P14, yielding considerably lower values for moist color.

The Chiatovich Flats profile (site P15; Fig. 2) reaches a depth of about 55 cm. Although the depth of this profile is relatively shallow, the Bt horizon is about 25 cm deeper than any of the other bedrock residual profiles found on younger geomorphic surfaces. Rubification is also much greater than for any of the other sampled soils. Hues of 7.5YR and 5YR dominate the entire profile from the surface to the soil–saprolite interface. Inasmuch as the Chiatovich Cirque and Middle Creek soils have lithologic and climatic characteristics similar to those of the planation surface, are relatively shallow, and are not rubified, the depth of weathering and reddening of the Chiatovich Flats profile is probably a function of duration of soil weathering.

Silt and Clay Distribution

General age trends exist between pedogenic clay and silt accumulation and first-order glacial events within the Chiatovich Creek basin (Fig. 7). The dominance of the silt fraction compared to sand and clay, as well as the common presence of silt in the upper horizons of many profiles, suggests that eolian processes are responsible for much of the observed silt, particularly in the younger profiles. Soils at sites P11C9, P21C7b, and P22C10 (Early Middle Creek) exemplify profiles with a high eolian input. Tills at these sites contain few fines, as this region is dominated by leucocratic, fine-grained aplite dikes (Fig. 2) that are highly resistant to weathering. These sites act as natural dust traps for eolian sediments during times of high influx rate. A relatively constant content of organic carbon suggests that the silt influx is both rapid and nonpedogenic.

Clay and silt enrichment do not discriminate Middle Creek from Chiatovich Cirque soils (Fig. 7). In contrast, clay and silt content of some Perry Aiken profiles is slightly greater and extends deeper than in Middle Creek soils. While the combined clay and silt content of the Middle Creek soils rarely exceeds 20 to 30%, Perry Aiken profiles have combined silt and clay contents that range

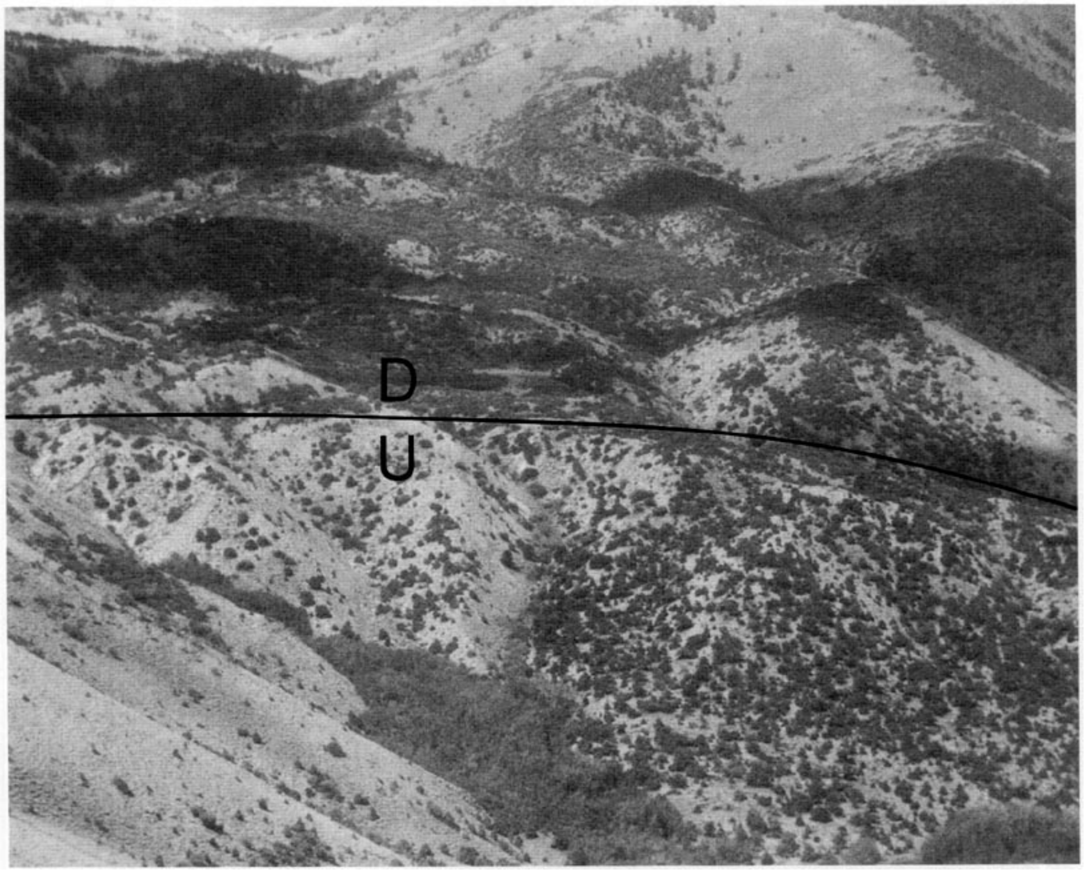

FIG. 5. Deposits of the Perry Aiken glaciation consist of a faulted sequence of massive recessional and terminal moraines. Several relict outwash channels are evident on the surface of the early Perry Aiken end moraine in the foreground. These have been uplifted along the fault shown in the center of photograph. Paired drainages on the western, downdropped block (D) can still be observed across the fault trend and are displaced to the north in the right center of the photograph. The older drainages on the uplifted moraine surface (U) have not been laterally offset, indicating that the principal fault displacement was vertical. This photograph was taken from a helicopter looking upbasin toward the west.

between 30 and 50% in the illuvial zone. These trends are most pronounced between the Early Perry Aiken (P8C13) and Early Middle Creek (P12) terminal moraines, where the clay accumulation reaches a maximum of 16% in the illuvial zone and extends to a depth of about 46 cm on the older Perry Aiken moraine; it only reaches a maximum of 11% and extends to a depth of about 25 cm on the younger Middle Creek moraine. Late Perry Aiken and Early Middle Creek moraines could not be separated on the basis of soil texture. However, Late Perry Aiken moraines have been extensively eroded. Soils at sites P19C5a (on a residual bedrock surface) and P23 (in till) are dissected by outwash channels apparently related to the Perry Aiken and Middle Creek advances.

More clay and silt occur in the Indian profiles than in those of Perry Aiken age (Fig. 7). In addition, the zone of clay accumulation extends deeper in the older soils. The particle-size data are less conclusive for sites P4 and P14, as both profiles represent multiple depositional episodes and their chronology and origin remain ambiguous.

The strongest age relationship, as shown by progressive clay accumulation, is seen in data from profiles on erosional surfaces associated with the Indian glaciation (sites P2C15, P3, P5C14, and P9; Fig. 2). All of these surfaces, with the exception of site P5C14, are preserved above the valley floor, and are therefore unlikely to have been disturbed by subsequent deposition. The extreme weathering of the clasts indicates that exposure to weathering and erosion may have been sufficiently long to have removed any preexisting fine-grained matrix. The residual soils formed on the Indian surfaces have more than twice as much clay (18 to 25%) as the Perry Aiken soils (8 to 10%) formed on similar erosional surfaces. Furthermore, clay content in the illuvial zone of the profile approaches or is greater than the silt content, suggesting that much of this clay is related to pedogenesis, and not simply the result of eolian influx, which is dominantly silt (e.g., P11C9, P21C7a, and P22C10).

Possible age trends of clay and silt accumulation in the Chiatovich Flats profile (site P15; Fig. 2) may be somewhat confounded by the effects of lithology and precipitation, as well as by eolian influx and erosion. Although the Chiatovich Flats profile does not exhibit a similar increase in clay relative to silt as do the Indian profiles,

FIG. 6. Residual till of the Indian glaciation is preserved along the confluence ridge of North and South Chiatovich creeks at site P9 (elevation 3050 m). The deposit stratigraphically lies ~75 m above the Perry Aiken moraines along the valley floor, indicating that it predates Perry Aiken glaciation. An extremely weathered adamellite till boulder (diameter >3 m) is present in the foreground. Photograph was taken from the summit of the confluence ridge of North and South Chiatovich creeks looking east.

this does not necessarily suggest that the Chiatovich Flats soil has undergone less pedochemical alteration than the Indian soils. The Chiatovich Flats soil is a residual soil and probably represents a remnant of extensive erosion. Furthermore, the high silt content (~40%) at site P15 is probably the result of eolian sedimentation along the northern, leeward range crest throughout the late Pleistocene. This accretion results in a particle-size distribution that tends to obscure progressive pedogenic clay accumulation over time.

Sand Fraction

A simple input model for the ratio of very coarse sand (VCS) to coarse sand (CS) plus medium sand (MS) predicts that the fine sand (FS) component of the sand fraction will increase with greater age. Only those fractions coarser than fine sand were used for this model to eliminate possible eolian components. By using the sand fraction as a relative-age parameter, the potential confounding effects of eolian influx are reduced. The numerator (VCS) has two possible input sources: gravels weathering to VCS and VCS weathering to finer VCS fractions, while the singular output is VCS weathering to CS + MS. In the same respect, there are four possible input sources for the denominator of the model (CS + MS): VCS weathering to CS, CS weathering to smaller CS fractions, CS weathering to MS, and MS weathering to smaller fractions of MS. The single output is MS weathering to FS.

The ratio of VCS/(CS + MS) should become progressively smaller over time, as the VCS is converted to finer sand fractions. Like other soil properties, this parameter eventually should approach a steady state under stable surface conditions. However, our data indicate that a steady-state condition has not been reached for the profiles measured in this study (Fig. 8).

The ratio of VCS/(CS + MS) decreases as a function of age within the time between the Chiatovich Cirque glaciation (~10,000 yr) and Indian glaciation (>200,000 yr). Although sample size is inadequate to demonstrate strong statistical relationships for the Chiatovich Cirque and Indian deposits ($N = 1$), the data show the potential application of this parameter for regions where eolian input is high (Fig. 8). The high standard deviations for the Middle Creek deposits may be due to weathering differences between the normal-phase adamellite tills of the extreme upper basin and the leucocratic adamellite tills at elevations lower than site P20C7a.

Organic Carbon

Organic carbon accumulation is of limited value as a relative-dating parameter for deposits spanning the Quaternary because it achieves a steady state within the soil profile over intervals of 200 to >10,000 yr (Birkeland, 1984). The time necessary for organic carbon to reach a steady state within a given soil profile is variable, and is greatly influenced by climate and vegetation.

Organic carbon content of the A horizons of Chiatovich Creek basin soils rarely exceeds 2%. The combination of the aridic to xeric moisture regimes and extremely permeable soils with low moisture-holding capacities inhibits plant understory development at most sites. Generally, organic carbon accumulation follows trends similar to that of plant cover, with soil profiles of the alpine zone having relatively higher percentages of A-horizon organic carbon. Organic carbon content is unusually high (>3%) for soil horizons containing charcoal fragments (e.g., P12, P4, and P10).

Profile Development Index

Morphologic development of a soil can be quantified using the profile development index (PDI) (Harden,

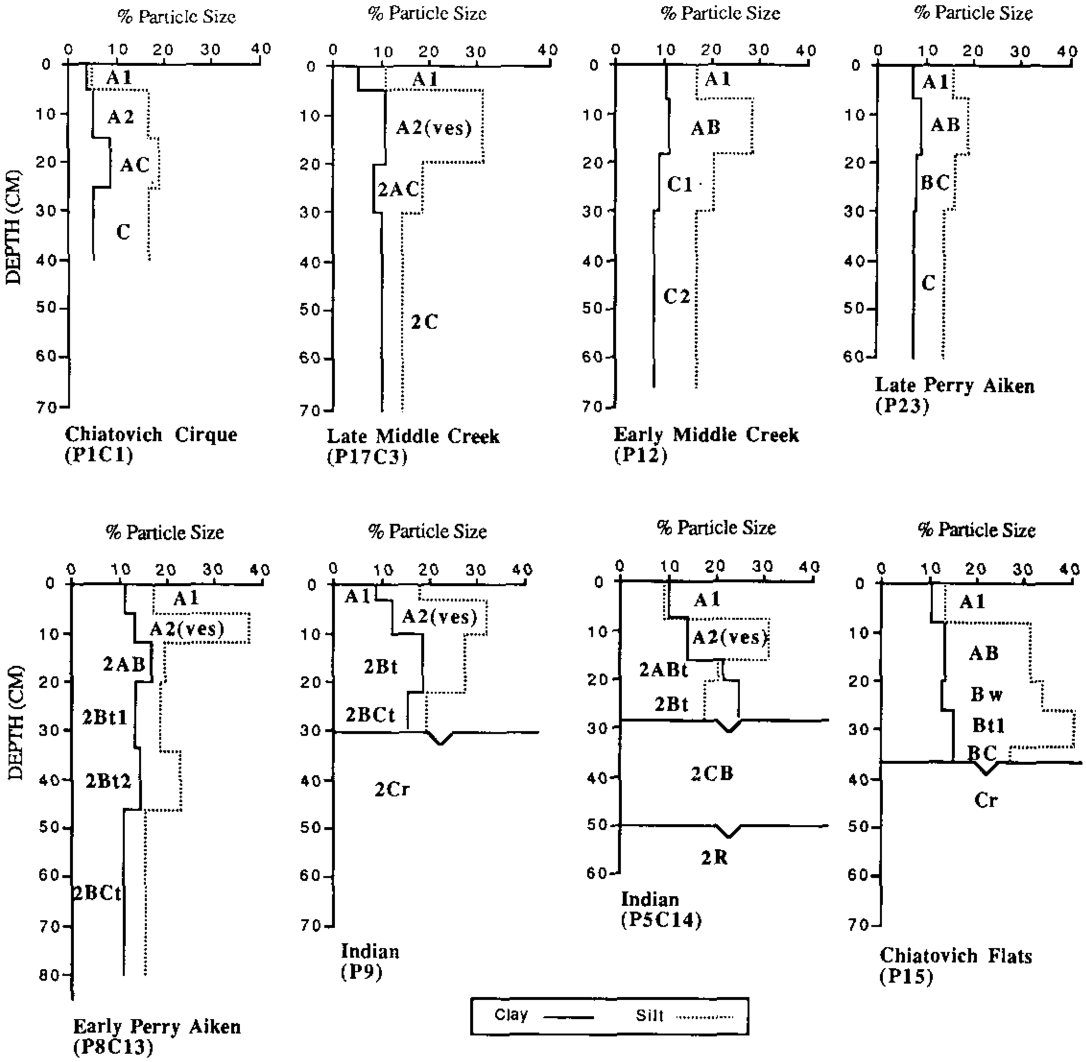

FIG. 7. Silt and clay trends for glacial depositional and residual soils of the South Chiatovich Creek Basin.

1982), which combines certain soil field properties and horizon thickness (Table 2). Calculated PDI values increase systematically with soil age for chronosequences in diverse climates and parent materials (e.g., Harden and Taylor, 1983; McFadden and Weldon, 1987). Although soils on glacial deposits in the Chiatovich Creek basin do not form an ideal chronosequence, soil profile indices appear to increase systematically with greater soil age (Table 2 and Fig. 9).

Increased organic-matter production and reduced decomposition rates (as expressed by increased melanization of the A horizon) result in higher PDI values than expected for the younger soils of the upper basin. Because soil development is generally weakly expressed in this basin, and comparative normalized melanization values are largely controlled by nontemporal factors between the upper and lower regions of the basin (i.e., precipitation, organic matter production, and decomposition), the overall effect of this parameter tends to confound age trends. Harden *et al.* (1991) have shown that melanization is best able to discriminate among relatively young soils.

When the effects of melanization are removed from calculated PDI values (to give adjusted PDI), age trends among glacial events are more clearly shown. Adjusted PDI values of the Late Middle Creek profiles are more than two times greater than those for the Chiatovich Cirque profile, whereas unadjusted PDI values for the same profiles are more similar. A slight increase in adjusted PDI values is evident as well between the late and early stades of the Middle Creek glaciation. This trend may be due to the early Middle Creek sites being more proximal to the zone of maximum effective precipitation (subalpine woodland zone) than sites of the later stade. With the exception of the pedon on the early Perry Aiken terminal moraine (site P8C13), Perry Aiken soils do not show a significant increase in adjusted PDI values compared to the Middle Creek soils (Table 2 and Fig. 9). The

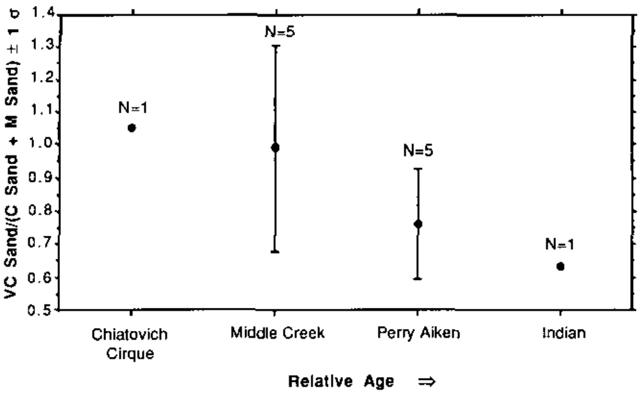

FIG. 8. Particle-size analyses of the sand fractions show that the ratio of VCS/(CS + MS) decreases as a function of age. Each data point on the graph represents a profile average of the respective sand fractions, calculated only for soils possessing a true till matrix.

TABLE 2

Soil Profile Indices of South Chiatovich Creek Basin, White Mountains, California–Nevada

Glacial stage and site number	PDI[a]	PDI (% melanization)[b]	Adjusted PDI[c]
Chiatovich Cirque			
P1C1	1.4	66.3	0.5
Late Middle Creek			
P16C2	1.6	32.4	1.1
P17C3	2.3	37.7	1.4
Early Middle Creek			
P20C7a	4.2	57.7	1.8
P12	4.4	46.2	2.2
Late Perry Aiken			
P23	4.1	46.5	2.1
Early Perry Aiken			
P7	3.4	38.1	2.1
P8C13	5.7	22.2	4.4
Late Indian			
P4	9.3	36.8	5.9
P14	11.6	52.6	5.5

[a] Profile development index (Harden, 1982) determined for each soil profile to the depth of assumed parent material (C horizon of site P1C1). Maximum values for morphologic properties used to calculate the profile index in this study were calculated on the basis of morphologic data reported by Harden (1982). PDI was only calculated for soil profiles possessing a fine matrix.

[b] *Represents that percentage of the total PDI that is attributed to the* melanization of the profile, and is a reflection of organic carbon accumulation.

[c] Reflects the soil profile development index after the short-term effects of organic carbon accumulation (melanization) are removed from the equation (Δ value). We believe that the adjusted PDI provides a more accurate representation of soil age than the standard PDI, which is susceptible to the confounding effects of varying organic matter production between the upper and lower basin.

extensive degree of stream incision and subdued surface morphology of the Perry Aiken moraines (Fig. 5) imply that their soil age is most likely much younger than the age of the deposit.

Although the genetic origin of the two fine-grained-matrix Indian profiles (site P4 and P14) is still uncertain, PDI values indicate that these profiles are better developed than those on Perry Aiken deposits. Excavations did not reach the assumed parent material for these Indian profiles; thus, it is likely that their PDI values would be even higher than those shown in Table 2. When the effects of melanization are removed from the calculated PDI values, the adjusted PDI values are consistent with the rock-weathering and stratigraphic data, and indicate that these two pedons probably are of similar age.

Iron and Aluminum Trends in Soils

Extractable iron (Fed) content was the only chemical parameter useful in discriminating age trends between glacial deposits (Table 3). Age trends exist for soils derived from till (Fig. 10) and bedrock residuum (Fig. 11); the latter soils show the strongest age trends. Although the Fed content of the Late and Early Middle Creek soils, from normal-phase adamellite (e.g., P17C3 and P20C7a, respectively), is greater than that of the Perry Aiken soils, from leucocratic phase adamellite (Fig. 10), the accumulation of Fed relative to the parent materials is greater in the Perry Aiken soils (Table 3). Differences between the Perry Aiken and Middle Creek sites might have been greater if the climate were the same throughout the basin. Furthermore, erosion of Fe-enriched B horizons from soils on Perry Aiken moraine crests may have led to a net transport of pedogenic Fed downslope, as in the Sierra Nevada (Birkeland and Burke, 1988) and Rocky Mountains (Meierding, 1984; Berry, 1987).

The high Feo/Fed ratios in the Chiatovich Creek soils indicate that much of the iron oxide is amorphous. The ratio for individual soil horizons shows similar profile patterns regardless of the inferred soil age. The relatively higher Feo/Fed ratios found in the Chiatovich Cirque soil and in surface horizons of all other soils of varying geologic age (data not shown) suggest that surficial trends of these two components are the result of weathering of Fe-bearing minerals to amorphous iron oxides in recently accumulated eolian sediments, although possibly the eolian sediments themselves contain dominantly amorphous iron oxides. The decrease in Feo/Fed ratios as a function of depth within the soil profile probably reflects mixing of a young eolian component with older glacial drift, as well as a progressive crystallization of amorphous Fe forms (since eolian sediment deeper in the profile is likely older than that near surface).

Profile content of Alo and Ald proved to be of little use for relative dating of glacial deposits (Table 3). Oxalate and dithionite are less-specific extractants of Al compounds than of Fe compounds (Birkeland, 1984). Ratios of Alo/Ald near 1 (Table 3) suggest that the oxalate and CBD extracted similar forms of Al in these soils. Further-

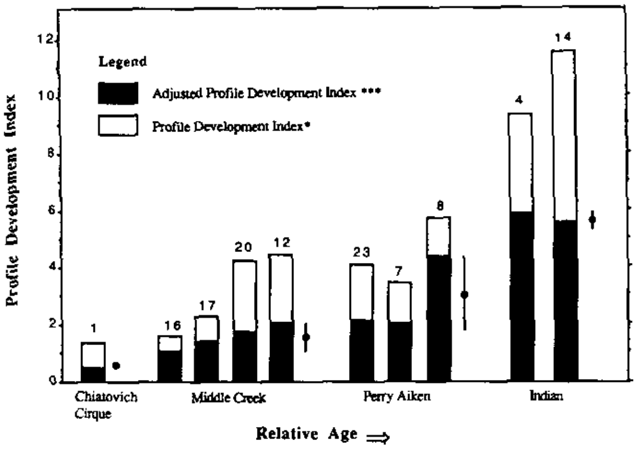

FIG. 9. Higher organic matter production and lower decomposition rates in the upper basin increase melanization and result in higher PDI than expected for the youngest soils. When the effects of melanization are removed (adjusted PDI), age trends between soil profiles are more clearly expressed. The mean $\pm 1\sigma$ error bars are shown beside each glacial stage. Numbers shown above the bars refer to soil site "P" numbers shown in Figure 2.

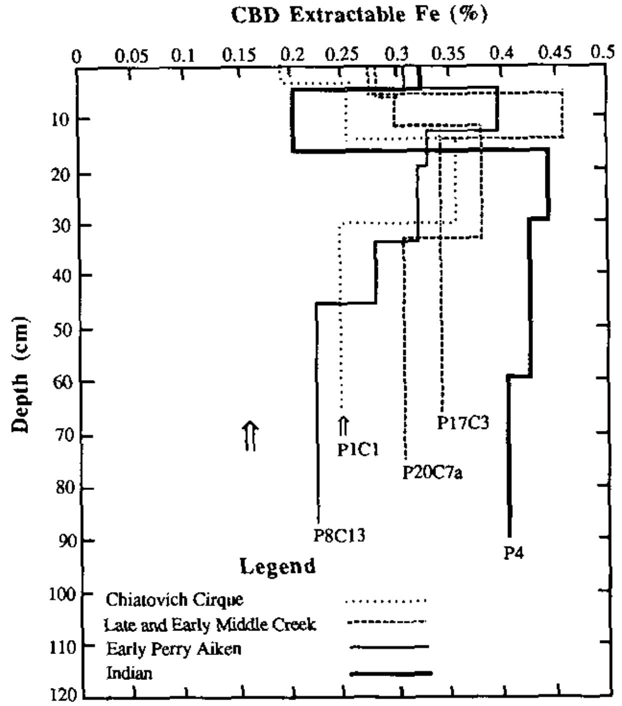

FIG. 10. CBD-extractable Fe distribution with depth in selected soils forming in glacial drift in the Chiatovich Creek Basin. Arrows show Fe content of assumed parent material representing till derived from both normal phase (small arrow) and leucocratic (large arrow). Note that the Chiatovich Cirque and Middle Creek soil profiles have formed in normal-phase adamellite tills, while Perry Aiken and Indian profiles have formed in leucocratic tills. When the iron content of the initial parent material is taken into consideration, relative-age trends are evident. In particular, the Indian profiles have relatively higher CBD Fe concentrations throughout a greater depth than the younger soils. Age trends between the Perry Aiken and Middle Creek soils are less clear.

more, the Al compounds that are differentially soluble and may be age dependent (i.e., allophane and imogolite) apparently are absent in these soils. The contribution of allophane or imogolite from weathering of late Holocene tephra is minimal. Weathering of 1100-yr-old rhyolitic tephra in semiarid northeastern California produced only trace amounts of amorphous aluminosilicate (Southard and Southard, 1989).

Rate Curve for Soil Development

A rate curve for soil development was constructed using adjusted PDI data and age estimates for glacial deposits presented by Swanson *et al.* (in press). The best-fit curve for the adjusted PDI data is similar to the weathering-rind rate curve constructed by Swanson *et al.* (in press), assuming a logarithmic relationship (Fig. 12). Like weathering-rind formation, the rate of soil formation decreases over time. The form of this curve is consistent with other rate curves derived for soil-development properties (Harden and Taylor, 1983; Birkeland, 1984). Climate and lithology probably increase soil development rates in the upper basin and thus increase the slope of the rate curve near the origin. Consequently, interpretations based on these data need to consider this probability when making comparisons of the rates of soil development between younger and older moraines.

DISCUSSION AND CONCLUSIONS

Soil parameters show that the soils developed on glacial deposits in Chiatovich Creek basin are not a true chronosequence. Nonetheless, some soil development trends related to soil age are apparent when lithologic and climatic variation is taken into account through a sequential-comparative approach (Swanson *et al.*, in press).

Although morphologic properties such as profile depth, horizonation, color, and soil texture do not discriminate among Late Wisconsin (Chiatovich Cirque, Late and Early Middle Creek) deposits, these properties did discriminate the Late Wisconsin deposits from older deposits (Perry Aiken, Indian, and Chiatovich Flats). These properties show more consistent age trends on the glacial-erosional surfaces than for soils derived from fine-matrixed tills. This may be due in part to trapping of eolian sediments in the coarse-textured till, but not on the smooth bedrock ridge crests. In future chronologic studies, residual soils on tills may provide more information on rates of soil development than the till-derived soil alone.

Sand fraction ratios were useful in minimizing the confounding effects of eolian influx on soil–age relationships. Our VC/(CS + MS) predicts that progressive weathering and breakdown of sand fractions in a soil can be used as a relative age indicator in settings where eolian influx rates are high and variable over space and time.

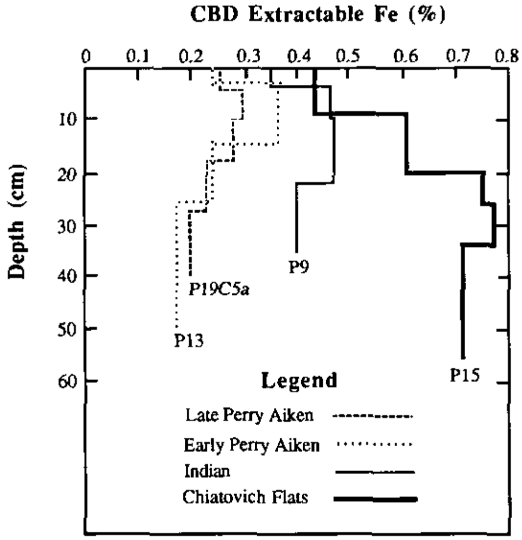

FIG. 11. CBD-extractable Fe distribution with depth in soils forming on residual bedrock surfaces associated with the Perry Aiken, Indian, and Chiatovich flats glaciations. A significant increase in Fed content and greater depth of Fed accumulation is evident in the Bt horizons of the oldest Pleistocene surfaces.

TABLE 3

Fe and Al Content of Glacial Deposits in South Chiatovich Creek Basin, White Mountains, California–Nevada

Glacial stage and site number	Content[a]					
	Fed	Feo	Ald	Alo	Feo/Fed	Alo/Ald
Chiatovich Cirque						
P1C1	1.1	1.0	0.7	1.0	0.94	1.53
Late Middle Creek						
P16C2	9.6	2.7	0.7	0.6	0.28	0.92
P17C3	7.8	0.4	0.7	0.6	0.06	0.92
P18	11.3	0.9	0.3	0.8	0.08	2.74
Early Middle Creek						
P20C7a	3.8	1.7	1.6	2.0	0.45	1.21
P21C7b	4.0	0.7	1.0	0.1	0.18	0.09
P12	5.5	1.8	1.3	2.5	0.33	1.86
Late Perry Aiken						
P19C5a (55 cm)[b]	4.0	0.9	0.2	1.0	0.22	5.37
P23	13.3	0.6	1.2	0.7	0.04	0.57
Early Perry Aiken						
P6C12	7.0	1.3	0.5	0.9	0.19	1.84
P8C13	10.2	1.2	1.3	1.0	0.12	0.78
P13 (27 cm)[b]	2.8	1.4	0.4	0.6	0.52	140.75
Late Indian						
P4	16.3	1.9	1.3	0.8	0.12	0.62
P14	14.2	2.2	1.1	0.1	0.15	0.06
Early Indian						
P9 (30 cm)[b]	7.3	1.0	1.0	1.1	0.13	1.10
P3C18 (10 cm)[b]	4.4	0.4	0.2	0.3	0.08	1.39
P2C15 (22 cm)[b]	4.1	0.6	0.3	0.7	0.16	2.40
P5C14 (28 cm)[b]	3.7	0.8	0.5	0.7	0.23	1.28
Chiatovich Flats						
P15 (55 cm)[b]	22.6	2.8	2.6	1.6	0.12	0.61

[a] Profile content of Fe and Al is calculated by summing the net increases of each component (weight percentage of each respective component minus that in the assumed parent material times the horizon thickness) to a standardized depth of 75 cm for profiles with a till matrix. Fe and Al trends of soils forming in bedrock residuum were calculated to the solum–Cr horizon interface. Parent material characteristics of till derived from normal-phase adamellite were assumed to be similar to the lowest measured Fe and Al values of the Chiatovich Cirque profile. Parent material characteristics of the leucocratic-phase adamellite were assumed to be similar to lowest measured Fe and Al values of the C horizon of the Late Perry Aiken soils.

[b] Designates that soil is formed in bedrock residuum. Numbers following the respective site names represent the depth to which Fe and Al content was calculated for each profile.

Our data substantiate the model: progressively older deposits had lower VC/(CS + MS) ratios. Further testing of this parameter is necessary to evaluate fully its effectiveness as a relative-dating technique. In particular, sample size should be increased, and sampling should be done at specific depths through the profile to evaluate variation within the profile.

Because soil development is extremely slow in the White Mountains, soil properties that reach a steady state over relatively short time intervals, such as organic matter content, dominate PDI values to the extent that age trends are inconsistent. This problem was minimized by removing the melanization value from PDI calculations, giving an adjusted PDI for each respective profile. The adjusted PDI values are more consistent with the weathering and morphostratigraphic data of the deposits than the unadjusted PDI, although in both cases apparent climatic and lithologic effects favor development in the Middle Creek soils. Our results show that PDI calculations should not include soil properties that reach steady state quickly relative to the time spanned by the deposits. Other soil properties, such as percentage gravels, carbonate development, and sand fractions, which may be more suitable for older glacial sequences, can be added to PDI calculations (i.e., Harden and Taylor, 1983; Harden *et al.*, 1991).

Of the four chemical parameters we measured (Fed, Ald, Fed, and Alo), only Fed content showed any consistent relationship with relative age. Inconsistent age trends of Feo are most likely the result of weathering of Fe-bearing minerals to amorphous iron oxides in relatively recent eolian sediments at virtually all locations throughout the basin and do not reflect a progressive crystallization of amorphous iron as a function of time. The Alo and Ald do not vary systematically with age because both oxalate and CBD probably extract similar forms of Al in these soils, and forms that are differentially soluble and possible age dependent are not present.

Soils and morphologic data clearly show that the surface age (age of the soil) of the Perry Aiken and older glacial deposits is likely to be considerably younger than the glacial stage that produced each deposit. The degree of stream incision and subdued morphology of the Perry Aiken moraines, as well as the lack of surface preservation of the Indian, Dyer, and Chiatovich flats deposits, support our speculation that surface erosion has greatly modified these older landforms. By contrast, the Middle Creek and Chiatovich Cirque moraines are sharp-crested and show little surface modification, indicating that soil

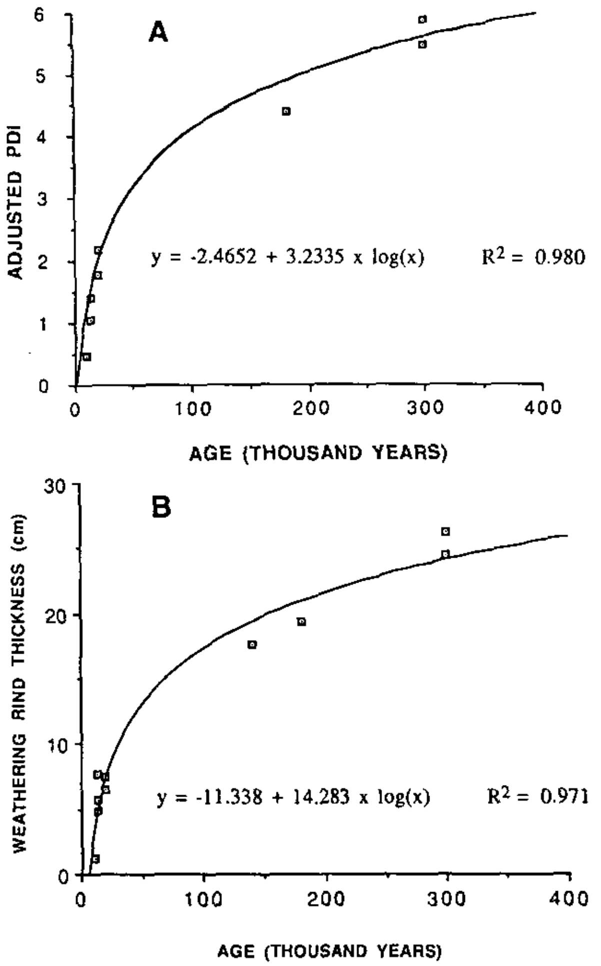

FIG. 12. Best-fit curve for the adjusted PDI (A) is similar to the weathering-rind rate curve (B), assuming a logarithmic form. Both weathering-rind and soil-formation rates decrease over time. Age estimates are taken from Swanson *et al.* (in press).

age is approximately equal to deposit age. Similar results have been found for glacial deposits in the eastern Sierra Nevada (Birkeland and Burke, 1988) and Rocky Mountains (Meierding, 1984; Berry, 1987), where pedologic data show that soils are being eroded from moraine crests, transported downslope, and deposited at footslope positions or beyond. Although surface erosion has not been quantified for the Sierra Nevada moraines, soil profile and chemical data (Birkeland and Burke, 1988) indicate that moraines as young as Tioga (isotope stage 2) show measurable soil erosion from crests. For the Rocky Mountains, Meierding (1984) has estimated about 10 m of moraine crest lowering on a typical Bull Lake (isotope stage 6) moraine, assuming an initial moraine morphology similar to that of Pinedale (isotope stage 2) moraines.

Soils and morphologic data have important implications for the application of surface-exposure dating techniques (i.e., cosmogenic isotopic dating and rock varnish cation-ratio and ^{14}C dating) to undated glacial sequences. An important assumption of surface-exposure dating is that the surface age closely approximates the deposit age, thus implying surface stability. However, the assumption of a "constructive" or "original" geomorphic surface may not be valid for regions where surface erosion equals or exceeds the rate of soil development. Furthermore, even where soil development is greater than the erosion rate (Berry, 1987; Birkeland and Burke, 1988), the surface of a landform is unlikely to be the same as, or even a minimum approximation of the age of the underlying deposit. This is especially true for older landforms. Consequently, ages based on surface-exposure dating need to be evaluated within the context of the erosional history of the dated surface before a numerical chronology can be established. Where erosion has been substantial, the surface exposure age of a till boulder may represent its exhumation age rather than its depositional age. Furthermore, surface degradation (i.e., granular disintegration and fire spallation) of the boulder may contribute to underestimation of the age of exposure (e.g., Dorn *et al.*, 1987, 1990; Phillips *et al.*, 1990; Bierman and Gillespie, 1991).

Interpretations of the eastern Sierra Nevada glacial sequence based on rock varnish cation-ratio dating in the Pine Creek drainage (Dorn *et al.*, 1987, 1990) and ^{36}Cl dating in the Bloody Canyon drainage (Phillips *et al.*, 1990) raise important questions regarding the application of these dating techniques for assigning numerical ages to older glacial deposits. The subdued morphology of the oldest moraines in the Bloody Canyon (i.e., Younger Tahoe, Older Tahoe, Mono Basin; Phillips *et al.*, 1990) and Pine Creek drainages (Tahoe and Rovanna; Dorn *et al.*, 1990), imply that substantial erosion has occurred. Consequently, an inferred minimum age of a glacial event may instead reflect the time when a boulder was exhumed. Unless the erosion rate or the magnitude of surface stripping is evaluated, surface-exposure ages will be inconclusive. Slope diffusion models, soil catena studies, and multiple measurements using several independent isotopic systems with different half-lives (J. Klein, personal communication, 1990), may help in evaluating derived numerical ages. Part of our long-term objectives for continued research in the White Mountains and eastern Sierra Nevada will be to address these important problems in a collaborative spirit.

It is apparent that soil-development properties and conventional relative-dating parameters will remain important research tools for understanding and interpreting landscape evolution. Data provided by these techniques can be employed not only to define relative chronologies, but also to assess surface degradation and its impact on surface-exposure ages. Furthermore, site selection strategy for establishing glacial chronologies should be reevaluated. A focus on relatively unstable moraine surfaces in tectonically active mountain systems may prove less productive than working with stable residual bedrock surfaces and associated low-relief outwash fans and terraces.

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