# Chemical Weathering Process on the Vantage Peak Nunatak, Juneau Icefield, Southern Alaska

by

Colin E. Thorn Department of Geography University of Illinois, Urbania 61801 *and* Juneau Icefield Research Program Foundation for Glacier Research Juneau, Alaska

John C. Dixon Department of Geography University of Arkansas, Fayetteville, 72701

Robert G. Darmody Department of Agronomy University of Illinois, Urbana, 61801

Reprinted from Physical Geography, 1984, 5, 2, pp. 111-131. Copyright © 1984 by V.H. Winston & Sons, Inc. All rights reserved.

# CHEMICAL WEATHERING PROCESSES ON THE VANTAGE PEAK NUNATAK, JUNEAU ICEFIELD, SOUTHERN ALASKA

John C. Dixon Department of Geography University of Arkansas Fayetteville, AR 72701 Colin E. Thorn Department of Geography University of Illinois Urbana, IL 61801

Robert G. Darmody Department of Agronomy University of Illinois Urbana, IL 61801

Abstract: On the Vantage Peak nunatak in the Juneau Icefield of southeastern Alaska, grus and soils display evidence of extensive chemical alteration in a self-evidently periglacial environment. Accompanying the alteration of bedrock to grus and soil is a decrease in grain size. Grus is dominated by very coarse sand while the soils are predominantly fine sand. Grain-size reduction is attributed primarily to mineral grain dissolution. Total chemical analyses show that alkali earths (calcium and magnesium) and alkalis (sodium and potassium) are lost as weathering progresses, while silicon and iron increase relative to resistant elements. Secondary clay minerals present in the grus and soils appear to have been derived from clay-size primary minerals. Vermiculite is the principal secondary clay mineral and appears to have formed by the alteration of biotite. Scanning electron microscopy shows that quartz and feldspars are primarily weathered by dissolution with no evidence of feldspar transformation to secondary clays. Superimposed on these weathering transformations is evidence of eolian processes. Chemical environment of the Vantage Peak nunatak and are Clearly an important component of the periglacial geomorphic process suite.

#### INTRODUCTION

Traditionally, periglacial landscapes have been viewed as environments in which physical or mechanical weathering is significantly more important than chemical weathering. In reality this is mainly an unverified assertion arising from the implicit assumption that chemical weathering rates are largely temperature dependent (Embleton and Thornes, 1979).

The supposed dominance of freeze-thaw weathering in periglacial regimes is under attack from two separate perspectives. First, the efficacy of freeze-thaw weathering is very much open to question (Hudec, 1973; White, 1976; Thorn, 1979; Hall, 1980; Thorn and Hall, 1980) because not only are the rates unknown, but even the physical principles involved are still open to debate (White, 1976; McGreevy, 1981; Fahey, 1983). Second, there has been a steady trickle of papers which quantitatively verify the importance of chemical weathering in cold climates, if an adequate water and hydrogen ion supply are available.

111

Physical Geography, 1984, 5, 2, pp. 111-131. Copyright © 1984 by V.H. Winston & Sons, Inc. All rights reserved. Chemical weathering is not necessarily slowed by low temperatures: Tamm (1924) pointed out that chemical process rates varied little between 2° and 15° C. In some instances, low temperatures should accelerate processes, a trait suggested by Williams (1949) who emphasized that as carbon dioxide is heavier than air, free water associated with snowpacks should be highly acidic and aggressive. Conceptually, this viewpoint was greatly strengthened by Reynolds and Johnson (1972) when they emphasized the importance of water and hydrogen ion supply, and not temperature, as the limiting factor in chemical weathering rates. However, Rapp's (1960) comparative study of the entire geomorphic process suite operating in Karkevagge, Swedish Lapland, probably did more than any other study up to that time to highlight the relative importance of chemical weathering in cold climates. Rapp's findings have subsequently been reinforced by more specialized studies, such as those of Caine (1979) on the weathering of rhyodacite samples placed on an alpine regolith surface, and Thorn (1976), who compared the chemical and mechanical contributions to transport within alpine nivation hollows.

Dixon (1983), working in the Colorado Front Range, has shown that chemical weathering in that periglacial environment is extensive. All silicate minerals in soils developed on glacial tills showed evidence of alteration. Biotite was pervasively altered to hematite, vermiculite, and smectite, while feldspars showed evidence of extensive dissolution.

Soil chemical analyses by Dixon (1983) showed that within the soil profiles most elements are relatively mobile. Potassium, magnesium, sodium, and calcium all showed evidence of removal from parent tills as soils progressively develop. Ferrous iron had been oxidized to ferric iron. Evidence of extensive chemical weathering in this periglacial environment was also provided from natural water chemistry which showed a substantial increase in total ion concentration over that of incoming precipitation.

The aim of the research reported in this paper is to determine the nature of chemical weathering processes operating on a nunatak in a self-evidently periglacial environment.

# RESEARCH SITE

The Vantage Peak nunatak is located in the Juneau Icefield of the Alaska-Canada Boundary Range between Juneau, Alaska, and Atlin, British Columbia (Fig. 1). The nunatak rises some 630 m above the Taku Glacier at a point where the glacier is 4 to 5 km wide. The general morphology of the nunatak is that of a horned peak on which the abutting cirques have been buried by the margins of several large valley glaciers. Several abandoned cirques and associated berm levels of unknown age occur on the flanks of the nunatak (Miller, 1976).

Miller (1976) has identified five berm levels which may be observed on Vantage Peak. They are eroded into the spur on which Camp 10 is located and produce a giant staircase effect on which treads and risers are readily distinguished (Fig. 2). Snow and firn rise high up on the north face of the spur, from which most of the samples analyzed in this study were collected; however, the crest and the south face are largely snowfree. The bedrock is weathered by exploitation of joints producing a smaller staircase effect. Vertical faces are generally 1-5 m high and 1-20 m wide. In some locations, the hori-



Fig. 1. Location of the study area. Lower left inset shows location of sample sites, numbers correspond to those of profile descriptions in text.



Fig. 2. Diagram of the Vantage Peak nunatak showing stepped nature of the topography. Landform settings of samples discussed in text are shown.

zontal surfaces are well sheltered and small pockets of soil have developed which are vegetated by tundra plants. Most outcrop and boulder surfaces exhibit some weathering rind development. Weathering sequences, from little altered rock through coarse detritus to grus and soil, are not uncommon.

The nunatak is one of the few places on the icefield where bedrock geology has been studied in any detail. Gilky (1958) estimated that the nunatak is composed of 50% granodiorite and 50% migmatite, with numerous intrusions the total area of which is hard to estimate. The granodiorite may be divided into aplitic granodiorite, dark pyroxene-rich granodiorite, and biotite-rich granodiorite. Subdivision of the migmatite is not appropriate as it is extremely heterogeneous. Among the widespread intrusions are amphibolite and diorite.

#### **RESEARCH METHODOLOGY**

#### Field Sampling

Field sampling focused on obtaining representative weathering sequences from the area mapped by Gilky (1958). Emphasis was placed on fresh bedrock, weathered surface bedrock, surface grus, buried grus, and associated soil mantles.

Soils were sampled down profiles at 5-10 cm intervals. In many cases it was not possible to ascertain if the parent material was bedrock or transported regolith. However, profiles were excavated as deeply as possible and coarse detritus was extracted from the base of the profile.

#### Laboratory Analyses

The texture of the grus and soil was determined using the methods of Day et al. (1956). Approximately 10 g of the <2 mm size fraction was split from a larger sample. The <2 mm fraction was separated from the coarser fraction by dry sieving. Organic matter was removed using a combination of decantation and hydrogen peroxide oxidation. The samples were then washed in distilled water to remove excess hydrogen peroxide (Soil Survey Staff, 1972).

Organic free samples were dispersed in sodium pyrophosphate and washed into a 1,000-ml cylinder and filled with water to 1,000 ml. Silt and clay contents were determined using the hydrometer method. Upon completion of the hydrometer determinations, the samples were passed through a 50- $\mu$ m sieve to remove the sand fraction. The sands were dried overnight at  $105^{\circ}$  C and then passed through a bank of sieves to separate and determine the abundance of the various sand fractions.

Chemical analyses of the organic free <2 mm size fraction samples were performed using atomic absorption spectrophotometry (AA) by Skyline Labs Inc., Denver. The samples were digested in hydrofluoric acid and the liquid was aspired into the spectrometer for analysis. The data obtained from the AA analysis were initially calculated as oxide weight percent, then recalculated as molar ratios (Colman, 1982; Birkeland, 1984).

The clay mineralogy of the grus and soils was determined by X-ray diffractometry. The clay-size fraction was separated by sedimentation. The clay was then concentrated by centrifuging at 1600 rpm for one hour. Following decantation of excess water, the slurry that remained was applied to heated ceramic plates and allowed to dry. This method produced well-oriented mounts.

X-ray analyses were performed on the samples after each of the following treatments: (1) air drying; (2) glycolation in an ethylene glycol atmosphere overnight; (3) heating at  $550^{\circ}$  C for two hours. The samples were then X-rayed on a Norelco diffractometer using Cu K a radiation with nickel filter.

The clay minerals were identified by observing changes in the basal reflections of treated and untreated samples. Methods of identification were based on those of Grim (1968), Birkeland (1969), Birkeland and Janda (1971), Mahaney (1974), and Shroba (1977).

A scanning electron microscope (SEM) was used to measure the shape of very fine sand-size quartz grains. Subsamples from the very fine sand fraction were separated from the  $\leq 2$  mm size fraction by sieving and were attached to specimen mounts with adhesive tabs and coated with gold-palladium. Ten grains from each of three horizons in a grus and soil profile were selected at random and photographed under the SEM. Grain sphericity was determined by measuring the long and intermediate axes of individual grains on SEM micrographs and determining the "inscribed circle sphericity" (Riley, 1941). Determination of inscribed circle sphericity (Oo) involves the measurement of inscribed circle diameter (i) and the circumscribed diameter (Dc) and calculation of Oo which is obtained by  $\sqrt{i}/Dc$ . All measurements were made to 0.5 mm. Shape distributions were analyzed by Analysis of Variance on rank transformed data. Transformation overcomes the problems of projection sphericity having a maximum value of 1.

The SEM was also used to determine the overall extent of weathering of quartz grains from three horizons of increasing depth in one grus and one soil profile. The same 10 grains from each sample were classified as 1 (highly weathered) through 5 (fresh or unweathered) by visual inspection using the criteria of Krinsley and Doornkamp (1973) and methods of Thorn and Darmody (1980).

Randomly selected very fine and coarse sand-size grains of feldspar and biotite were also examined visually with the SEM to determine the nature of the processes responsible for mineral grain weathering. Feldspar grains were examined to determine the presence or absence of etching and its extent and orientation. Biotite grains were

#### DIXON, THORN AND DARMODY

examined for evidence of etching, exfoliation along cleavage planes, and clay or iron oxide development.

# MATERIALS

Weathering profiles of grus and soil were excavated by hand in order to examine the full spectrum of weathering products. Sites were selected where maximum depth could be achieved in a diversity of lithologic settings. Surface and near-surface grus samples were also collected from the summit of Taku B (Site 5, Fig. 1). Profile descriptions are as follows:

# 1. Soil Profile 8-5-80

Elevation: 1 350 m; Aspect: south; Drainage: well-drained; Slope: 1°; Vegetation: tundra herbs and grasses; Parent material: biotite-rich granodiorite; Landform: Summit of Taku B.

0-5 cm. Dark reddish-brown (SYR 2/2) fine sandy loam with weakly humified organic matter; few roots; no rock fragments; clear wavy boundary.

5-10 cm. Dark reddish-brown (5YR 2/2) fine sandy loam with occasional very dark stringers; no rock fragments; clear wavy boundary.

10-15 cm. Dark brown (7.5YR 3/2) fine sandy loam; no roots; no rock fragments; abrupt smooth boundary.

15-20 cm. Dark brown (7.5YR 3/2) gravelly sandy loam; no roots; no coarse stones; gradual wavy boundary.

20-25 cm. Dark brown (10YR 4/3) gravelly sandy loam; no roots; clear wavy boundary.

25-30 cm. Very dark brown (10YR 2/2) sandy loam; no roots; no coarse stones; bedrock not reached.

#### 2. Grus Profile 8-9-80

Elevation: 1230 m; Aspect: south; Drainage: well-drained; Slope: 1°; Vegetation: none; Parent material: pyroxene-rich granodiorite; Landform: Level 2 berm.

0-5 cm. Very dark brown (10YR 2/2) gravelly sandy loam; no roots; clear wavy boundary.

5-10 cm. Not sampled.

10-20 cm. Dark brown (10YR 3/4) loamy sand; no roots; no coarse stones; bedrock not reached.

#### 3, Soil Profile 8-9-80

Elevation: 1050 m; Aspect: south; Drainage: well-drained; Slope: 1°; Vegetation: tundra herbs and grasses; Parent material: pyroxene-rich granodiorite; Landform: C10 level berm.

0-8 cm. Very dark gray-brown (10YR 3/2) sandy loam; humified organic matter; few roots; no coarse stones; abrupt smooth boundary.

8-9 cm. Very dark gray-brown (10YR 3/2) coarse sandy loam; no roots; no coarse stones; abrupt smooth boundary.

#### 116

9-14 cm. Very dark brown (10YR 2/2) sandy loam; no roots; no coarse stones; clear wavy boundary.

14-19 cm. Dark brown (10YR 3/3) coarse sandy loam; no roots; no coarse stones; clear smooth boundary.

19-38 cm. Pale red (2.5YR 6/2) fine sandy loam; no roots; no coarse stones; bedrock not reached.

#### 4. Soil Profile 8-11-80

Elevation: 1230 m; Aspect: south; Drainage: well-drained; Slope: 1°; Vegetation: tundra herbs and grasses; Parent material: diorite; Landform: Level 2 Berm.

0-5 cm. Very dark gray-brown (10YR 3/2) coarse sandy loam; humified organic matter; few roots; diffuse wavy boundary.

5-10 cm. Very dark gray-brown (10YR 3/2) gravelly sandy loam; few roots; diffuse wavy boundary.

10-15 cm. Very dark gray-brown (10YR 3/2) gravelly fine sandy loam; no roots; diffuse wavy boundary.

15-20 cm. Very dark gray-brown (10YR 3/2) gravelly fine sandy loam; no roots; bedrock not reached.

# **RESULTS AND DISCUSSION**

### Particle Size

Particle-size distributions of grus and soil profiles are shown in Table 1. Surface grus samples from a diversity of lithologic environments are dominated by sand with substantially smaller quantities of silt and clay. Silt contents range from 4.0-15.9% and clay contents from 1.1-8.4% with most samples containing less than 5.0% clay. The sand fraction is dominated by very coarse sand (1,000-2,000  $\mu$ m). The abundance of very coarse sand and the paucity of silt and clay are a reflection of the early stage of bedrock breakdown which grus represents. Within grus profile 8-9-80, there is a rapid decrease in the abundance of very coarse sand with depth and an accompanying relative increase in silt and clay. This fining of the grain-size distribution may be due to greater weathering at depth or to the translocation of fine grain particles deeper in the profile.

Grain-size distributions in soil profiles 8-5-80 and 8-9-80 display a very different pattern than those of the grus. The soil profiles are distinguished by substantially smaller quantities of very coarse sand and substantially greater abundance of finer grain-sizes. In soil profile 8-11-80, however, the surface horizon is dominated by very coarse sand while the deeper horizons display grain-size distributions similar to the other soil profiles examined. The very coarse sand-dominated surface horizon may be the result of eolian deflation of finer grain-size material. Accompanying the lower very coarse sand contents of the soil profiles examined is a greater abundance of finer size fractions than is present in the grus. Silt contents of the soils range from 14-45% while clay contents range from 3.7-10.8%.

The most noticeable characteristic of the grain-size distributions of the soils examined is the predominance of fine to medium sand and coarse silt. In soil profile 8-5-80

Table 1. Fine Earth Particle-Size Distribution (%) of the <2-mm Size Fraction, from Soil and Grus Profiles on Vantage Peak Nunatak

	ν.co. 1,000-2,000 μm		46.3	38.0	51.4	43.9		1.1	1.1	1.0	1.2	2.9	2.9		43.7	18.6	17.6		5.5	13.5	8.2	19.8	8.0		35.7	6.2	2.8	2.8
	co. 500-1,000 μm		16.8	18.2	16.4	19.0		6.1	5.3	4.8	6.0	8.5	6.6		15.8	16.4	15.9		11.8	15.2	12.6	15.7	9.2		12.7	14.1	8.4	6.8
Sand	т. 250-500 µт		15.2	16.1	12.2	12.9		22.0	14.8	17.2	21.8	20.6	21.8		12.0	19.2	17.8		14.2	12.1	13.8	15.9	10.4		11.2	15.7	13.6	14.3
	f. 100-250 μm		10.6	12.3	8.6	10.3		35.4	35.2	35.2	32.8	28.4	26.4		8.8	14.2	17.6		11.9	12.5	12.3	12.0	13.3		10.8	15.9	18.1	22.1
	ν.f. 50-100 μm	us samples	4.3	5.5	3.6	5.0	profile 8-5-80	3.2	12.4	16.3	13.6	12.6	12.4	profile 8-9-80	6.5	12.3	10.1	profile 8-9-80	10.7	12.1	12.3	11.8	10.3	profile 8-11-80	6.5	11.6	14.5	15.9
	со. 20-50 µт	টা	0.7	1.6	1.8	1.8	Soil	22.0	11.6	11.1	10.2	11.3	10.9	Grus	3.0	6.9	7.4	Soil	26.0	10.6	24.4	12.5	12.3	Soil	4.9	16.5	16.4	17.2
Silt	т. 5-20 µт		3.6	4.2	3.7	4.3		3.3	5.1	3.6	3.6	4.1	3.8		5,5	5.5	6.7		11.9	10.1	4.5	4.3	19.9		6.5	7.4	10.6	7.1
	f. 2-5 μm		ł	1.9	0.3	1.7			3.8	2.5	2.5	3.2	3.6		0.3	I	1.8		0.4	3.6	1.2	0.8	12.9		3.3	1.8	7.3	5.5
Clay	<2 µm		2.8	3.1	2.0	1.1		7.1	6.7	8.3	8.3	8.4	8.3		4.4	7.2	5.1		7.6	8.3	10.8	7.2	3.7		8.4	0.8	8.3	8.3
	Depth(cm)		0-5	5-10	5-8	0-5		0-5	5-10	10-15	15-20	20-25	25-20		0-1	1-5	10-20		0-8	8-9	9-14	14-19	19-38		0-5	5-10	10-15	15-20
	Sample No.		18	1 <b>A</b>	3 <b>A</b>	4 A			2	ę	4	s	6		7	ť	4		7	, 00	6	10	11		ŝ	4	5	6

each horizon sampled is dominated by fine sand which decreases in abundance with depth. The dominance of fine sand may be the result of the breakdown of coarser grain sizes by the combined effects of physical and chemical weathering or it may be in part the result of eolian additions as suggested by a number of authors for similar size material in soil in Norway (Ellis, 1980).

The coarse-to-medium silt observed in soil profile 8-9-80 may also be eolian in origin. Similar size material has been attributed to such an origin elsewhere in Alaska by Swine ford and Fry (1945), Péwé (1951), and Rieger and Juve (1961).

#### Geochem istry

Chemical changes occurring as a result of bedrock weathering to grus and soil were determined from changes in the molar ratios of mobile to resistant oxides. These ratios assume that the resistant oxides of Fe, Al, and Ti are immobile in the weathering environment (Colman, 1982), and therefore any changes in the ratios that do occur reflect the extent to which the more mobile oxides of Ca, Mg, Na, and K are removed. In general as weathering progresses, oxide molar ratios decrease as greater quantities of mobile oxides are removed from the weathering profile (Birkeland, 1984). The molar ratios CaO + MgO:  $R_2O_3$  ( $R_2O_3 = Fe_2O_3 + Al_2O_3 + TiO_2$ ),  $Na_2O + K_2O:R_2O_3$ , Total bases (CaO + MgO +  $Na_2O + K_2O:R_2O_3$ , SiO<sub>2</sub>:  $R_2O_3$  and  $Fe_2O_3:Al_2O_3$  (Table 2) were determined to evaluate most completely the extent of chemical changes accompanying bedrock breakdown in this periglacial environment.

Alkali earth: resistate (CaO + MgO:  $R_2O_3$ ) ratios were determined for grus and soil samples collected systematically down profiles. Accompanying the alteration of fresh mafic bedrock to grus (Profiles 8-5-80 and 8-9-80; Table 2) is a decrease in this ratio, suggesting a loss of calcium and magnesium. However, in the surface horizons of these two profiles there is an increase in the ratio compared to that of deeper horizons and fresh bedrock. These alkali earth increases are accompanied by an abundance of very coarse sand compared to lower horizons in the profiles. This suggests that the increase in the alkali earths may be due to the concentration of coarse, and presumably relatively fresh, mineral grains as a result of the removal of fine-grained material by eolian processes. A second explanation for the increase in the alkali earths could be eolian addition, although the grain-size data do not support such an explanation. A third explanation which may account in part for the observed increase is the addition of aerosolic marine salts. In two soil profiles (8-5-80 and 8-11-80), there is a systematic decrease in the ratio with decreasing depth below the surface, suggesting progressively greater weathering toward the top of the profiles. Such a trend is to be expected as more water and enhanced leaching occur in this part of the soil profiles. In soil profile 8-9-80 there is a decrease in the ratio from the lowermost horizon sampled to the middle horizon, suggesting an increase in weathering toward the surface of the profile. However, the surface horizon reflects an increase in the ratio, suggesting an eolian influence. Grain-size analyses show an abundance of coarse silt in this horizon compared to those at depth. Scanning electron microscopy reveals the presence of volcanic ash in some of the soils and this may account for the abundance of fine-grained material in the surface horizon of the profile as well as the associated increase in the alkali earth:resistate ratio. Further, the study area is only six miles from the ocean and in the direct line of prevailing winds, which may introduce aerosolic marine salts

Sample No.	Depth (cm)	$\frac{\text{CaO} + \text{MgO}}{\text{R}_2\text{O}_3*}$	$\frac{Na_2O + K_2O}{R_2O_3}$	Total Bases R2O3	$\frac{SiO_2}{R_2O_3}$	$\frac{Fe_2O_1}{R_2O_3}$
		Grus pro	file 8-5-80			
1B	0-5	1.46	0.17	1.61	3.44	0.51
1A	5-10	1.08	0.19	1.27	3,38	0.33
1D	fresh bedrock	1.12	0.23	1,34	3.35	0.35
		Soil prof	ile 8-5-80			
1	0-6	0.92	0.15	1.11	2,86	0.47
3	10-15	0.96	0.14	1,14	4.78	0.45
6	25-30	1.04	0.20	1.20	3.16	0.44
		Grus pro	file 8-9-80			
2	0-1	1.33	0.21	1.57	3,73	0.37
3	1-5	1.29	0.21	1.44	3,51	0.43
4	10-20	1.21	0.19	1,43	3,59	0.42
1	fresh bedrock	1.24	0.20	1.45	3,55	0.42
		Soil prof	ile 8-9-80			
7	0-8	0.23	0.64	0.81	8.82	0.08
10	14-19	0.14	0.63	0.80	8.50	0.08
11	19-38	0.19	0.63	0.75	7.16	0.09
6	fresh bedrock	1.15	0.62	1.35	3.31	0.27
		Soil profi	le 8-11-80			
3	0-5	0.33	0.60	0.88	7.50	0.13
4	5-10	0.61	0.39	0.18	5,41	0.19
6	15-20	0.68	0.37	1.08	4.98	0.19
		Bedrock	8-14-80			
2A	fresh aplite	0,15	0.85	0.97	9.51	0.07
2B	weathered aplite	0.15	0.77	0.92	9,59	0.07

 
 Table 2. Molar Ratios of Oxides for Bedrock and Associated Soils and Grus from the Vantage Peak Nunatak

to the weathering and soil system. Spatial discontinuities in eolian and aerosolic inputs apparently occur in the study area and this is consistent with observations made by other workers in mountain environments (Thorn and Darmody, 1980; Burns and Tonkin, 1982).

A comparison of fresh and apparently weathered aplitic granodiorite shows no change in the alk ali earth:resistate molar ratio, suggesting no removal of calcium and magnesium as a result of weathering, or no increase in  $R_2 O_3$ .

Alkali:resistate  $(Na_2O + K_2O; R_2O_3)$  ratios show similar trends to the alkali earth:

resistate ratios. In the two grus profiles alkalis show a depletion as bedrock alters to grus. Again, in one of the grus profiles (8-9-80) there is an increase in the ratio in the surface horizon presumably due to eolian processes. The three soil profiles show variable trends in this ratio. In soil profile 8-5-80, alkalis show removal from the profile, while the other two show an accumulation. No consistent weathering trend is apparent, probably a result of masking by eolian and aerosolic additions. A comparison of the fresh and weathered aplitic granodiorite shows a decrease in the ratio, reflecting a loss of these elements compared to the resistates.

Total bases (CaO + MgO + Na<sub>2</sub>O + K<sub>2</sub>O):resistates (R<sub>2</sub>O<sub>3</sub>) ratios show similar trends to the alkali earths:resistate ratios. In the two grus profiles, there is a decrease in the ratio from fresh to grusified bedrock. The surface horizons of the two profiles, however, show an increase in the ratio, suggesting eolian addition or concentration. Soil profile 8-5-80 displays a progressive decrease in the ratio with decreasing depth below the surface. For this particular profile similar trends were observed with respect to alkali earths and alkalis. Soil profiles 8-9-80 and 8-11-80 show evidence of base removal in the lower part of the profile, but the surface horizons show evidence of base addition. This apparent addition may be the result of eolian/aerosolic salt additions, surficial eolian reworking, or winnowing of fines and associated concentration of fresh, coarse material. The weathered aplitic granodiorite shows a decrease in the ratio compared to fresh bedrock suggesting removal of bases as a result of weathering.

Silicon: resistate ratios  $(SiO_2 : R_2O_3)$  increase as fresh bedrock alters to grus and soil. This can be seen by comparing the ratio for bedrock with that of the deepest (and presumably least weathered) horizon sampled. In some profiles there is a substantial increase in the ratio in the surface horizon (soil and grus profiles 8-9-80 and soil profile 8-11-80). In soil profile 8-9-80, the sharp increase in the ratio in the surface horizon is accompanied by an abundance of coarse silt suggesting possible colian influences. A similar increase in the ratio in the surface horizon of grus profile 8-5-80 is not, however, accompanied by an increase in the silt-size fraction. The substantially lower ratio in the surface horizon of soil profile 8-5-80 and the increase in the middle horizon may be due to silicon leaching. The presence of etch pits in some quartz grains (Fig. 3) observed under the SEM suggests that under favorable conditions dissolution of quartz does occur. Weathered aplite also shows a slight increase in the ratio compared to that of the fresh bedrock.

The iron:alumina ( $Fe_2O_3:Al_2O_3$ ) ratio shows considerable variability. However, there is an overall tendency for  $Fe_2O_3$  to remain constant or increase slightly with increasing weathering. In two of the profiles examined (grus profile 8-9-80 and soil profile 8-1 1-80), however, there is a decrease in the ratio in the uppermost horizon. Soil profile 8-9-80 shows a pronounced decrease in the ratio in the soil compared to that of the fresh bedrock. No change in the ratio was observed for the weathered aplite compared to the fresh bedrock. Where  $Fe_2O_3$  does increase in the soil and grus profiles it is interpreted to be the result of the oxidation of iron-rich minerals, especially biotite. Visual examination of rock fragments in soil pits showed pervasive iron staining, confirming such an interpretation. Where the ratio decreases, the addition or concentration of fresh aluminosilicates by colian processes is a likely explanation.

A comparison of the ratios of mobile to immobile elements in grus and soil compared to fresh bedrock suggests that bases are lost from the weathering and soil systems. Iron-rich minerals appear to be oxidized and silicon increases. However, the

#### DIXON, THORN AND DARMODY





pattern of weathering displayed by the grus and soil profiles is apparently masked in part by the effects of eolian processes. As a result, the observed changes in elemental ratios represent minimal amounts of weathering.

#### Clay Mineralogy

The principal minerals present within the clay-size fraction are kaolinite, vermiculite, biotite, plagioclase, quartz, and some smectite (Table 3). The dominant minerals in the clay-size fraction are quartz and plagioclase (Table 3). As these are primary rock-forming minerals, their abundance in this size fraction suggests that they have been derived from the mechanical breakdown or dissolution of larger grains. The increase in the abundance of feldspar, in particular, in the surface horizon of two profiles may be a reflection of the enhanced mechanical breakdown in the upper parts of the profile, or it may be a reflection of eolian addition or concentration.

The secondary clay minerals dominating the clay-size fraction are kaolinite and vermiculite (Table 3). Kaolinite occurs in small to trace amounts and commonly shows uniform abundance with depth in the profile. However, in two profiles (soil profile 8-5-80 and grus profile 8-9-80) there is a slight increase in the relative abundance of this mineral in the surface horizon compared to that at depth.

Kaolinite in soils and weathering profiles may be derived from a number of sources, including the weathering of feldspars, mica, and smectite. Examination of the patterns

Sample No.	Depth (cm)	Vermiculite	Kaolinite	Biotite	Plagioclase	Quartz	Smectite
			Grus sample	s			
18	0-5	tr <sup>1</sup>	tr		++	++++	
14	5-10	tr	tr		++	++++	
3A	5-8	tr	tr	tr	++	++++	
4A	0-5		tr	tr	++	++++	+
		So	oil profile 8-5	-80			
1	0-5	+	+		++	++++	
2	5-10	+	tr		+	++++	
3	10-15	+	tr		+	++	
4	15-20	tr	tr		+	+++	
5	20-25	+	tr	••••	++	+	
6	25-30		tr		+	++	
		Gr	us profile 8-9	9-80			
2	0-1	+	+		++	++++	
3	1-5	+	tr	tr	+	++++	
4	10-20	tr	tr		+	++++	
		So	il profile 8-9	-80			
7	0-8	++++	+		+	++++	
8	8-9	+++	+	•	+	++++	
9	9-14	+	+		+	++++	••••
10	14-19	tr	+	+	' +	++++	
11	19-38		+	+	+	+++	
		Soi	l profile 8-1	1-80			
3	0-5	+	+		+	+++	
4	5-10	÷	ŧ-		+	+++	<b></b> .
5	10-15	+	+		+	+++	
6	15-20	++	+		+	++++	
1. tr =	0-5 cps. (peak	height in count	s per second	s)			
+ =	6-15 cps.						
++ =	16-25 cps.						
+++ =	26-50 cps.						
++++ =	51-100 cps.						

# Table 3. Clay Mineralogy of the <2-µm Grain-Size Fraction of Soils and Grus from the Vantage Peak Nunatak

of distribution of the relative abundances of kaolinite and the above-mentioned minerals provides no evidence of the *in situ* formation of kaolinite. Rather, given the small amounts present in the profiles, an eolian source for this mineral is likely.

Vermiculite occurs in trace to very abundant amounts in the grus and soil profiles. In general, the abundance of this mineral increases in the upper part of the profiles. Vermiculite is an alteration product of biotite as a result of the loss of potassium from

Sample No.	Depth (cm)	Weathering Index <sup>1</sup>	Circle Sphericity		
	9	Soil profile 8-5-80			
1 3	0-5 10-15	4.3 <sup>2</sup> 3.4	.74 .76		
6	25-30	4.8	.86		
	G	rus profile 8-9-80			
2	0-1	4.5	.73		
3	1.5	4.2	.74		
4	10-15	4.3	.76		
<ol> <li>Mean of 10 gr</li> <li>1-highly weat</li> <li>2-25% unweat</li> <li>3-50/50 weath</li> <li>4-25% weath</li> <li>5-essentially</li> </ol>	ains thered athered thered/unweathered ered un weathered				

 Table 4. Weathering Classification and Inscribed Circle Sphericity of Very

 Fine Sand-Size Quartz Grains

the crystal lattice and the oxidation of iron 2+ to iron 3+ (Douglas, 1977). A comparison of the pattern of distribution of vermiculite and biotite abundances suggests that biotite is altering to vermiculite. In general, where there is a marked decrease in biotite abundance, there is an accompanying increase in vermiculite. Where vermiculite is present in the profile and no biotite occurs, it is suggested that all the biotite has been altered to vermiculite. Differences in the relative amounts of vermiculite in the profiles where biotite is absent are interpreted to be due to variations in the initial amounts of biotite present.

#### Scanning Electron Microscopy

Using the criteria of Krinsley and Doornkamp (1973) and the methods of Thorn and Darmody (1980), a weathering index based on the proportion of weathered to nonweathered very fine sand-size quartz grains was developed for one grus and one soil profile. For samples collected from soil profile 8-5-80, the uppermost horizons are apparently slightly more weathered than the lowest horizon. The 10 samples examined from the lowest horizon have a mean ranked weathering index of 4.8 while the middle and upper horizons have indices of 3.4 and 4.3, respectively (Table 4). The slightly higher value for the surface horizon compared to the middle horizon may be attributed to relatively fresh quartz grains being added or concentrated by eolian processes.

Quartz grains in the grus profile show an overall lower degree of weathering than those in the soil as was to be expected. The bottom horizon sampled in the grus profile displays a mean weathering index of 4.3 while the middle and upper horizons have indices of 4.2 and 4.5, respectively. Again, the slightly higher value in the surface horizon may be due to eolian addition or concentration of relatively fresh material.



Fig. 4. Strongly aligned, cleavage plane controlled, dissolution pits on the surface of a coarse sand-size plagioclase feldspar grain. Length of the scale bar is 5  $\mu$ m.

Riley Inscribed Sphericity was calculated for the very fine sand-size quartz samples from each horizon of the profiles to determine whether there were any changes in sphericity with depth as result of weathering. In the soil profile the only significant difference in sphericity, following Analysis of Variance of ranked scores, was between the lowest and the middle horizons sampled. The quartz grains from the lowest horizon were significantly less rounded than those in the middle and upper horizons of the profile (Table 4). This difference is interpreted to be the result of increased weathering higher in the profile, which is consistent with the weathering indices discussed above. No significant differences in sphericity were found to exist between any of the horizons in the grus profile. This trend is consistent with the high weathering index values of th is profile.

Surface textures of selected very fine and coarse feldspar and biotite grains were examined to determine the weathering processes responsible for the chemical and mineralogical changes outlined earlier in this paper. Feldspars commonly displayed solution pitting. Pitting was found to be aligned (Fig. 4) or random (Fig. 5), presumably depending on the relative influence of cleavage and chemical inhomogeneities. Although chemical variability of the feldspars was not specifically determined, it is likely that the nonaligned weathering pits correspond to calcium-enriched zones of the feldspars. Further evidence of chemical weathering of feldspars is seen in the rounding of grains (Fig. 6) and the scaling of some grain surfaces at high magnification (Fig. 7).

A diversity of textures and structures can be seen on individual fine and coarse



Fig. 5. Dissolution pits on the surface of a coarse sand-size plagioclase feldspar grain. Pits are randomly distributed, indicating little cleavage plane control. Length of scale bar is 5  $\mu$ m.



Fig. 6. Coarse sand-size plagioclase feldspar grain showing pronounced rounding, presumably as a result of the effects of dissolution. Length of the scale bar is  $100 \,\mu$ m.





sand grains of biotite. Some grains show evidence of etching along their cleavage planes (Fig. 8). This etching may be due to the release of potassium and magnesium from interlayer positions in the lattice. Many grains show evidence of exfoliation along basal cleavage planes (Fig. 9). This structure has been interpreted by previous workers (Isherwood and Street, 1976; Dixon 1983) to be the result of hydration; however, it may also be due to hydrogen peroxide sample treatment. Some biotite grains show evidence of mechanical breaking and bending, which may be due to frost action or to sample treatment.

## CONCLUSIONS

Grain-size distributions of grus and soil profiles studied suggest that grus is essentially derived from the mechanical breakdown of bedrock. The processes responsible for bedrock disintegration may be frost, biotite exfoliation due to hydration, clay formation and associated expansion along fractures and grain boundaries, or dissolution along grain boundaries. No conclusive evidence for biotite exfoliation could be found and no evidence of clay formation from primary silicates was available from the coarsesize fraction. Evidence of mechanical breakage of biotite grains was found in the sandsize grains as was evidence of feldspar-grain dissolution. These latter two processes may together contribute to bedrock grussification.

Grain sizes in the soils examined were substantially finer than that of the grus. This



Fig. 8. Very fine sand-size biotite grain showing etching along cleavage planes as a result of dissolution. Length of the scale bar is  $10 \,\mu$ m.



Fig. 9. Coarse sand size biotite mica grain showing exfoliation of basal cleavage planes as a result of hydration or  $H_2O_3$  swelling. Length of the scale bar is 5  $\mu$ m.

pattern may be due to the combined effects of a reduction in grain size due to mechanical break down and dissolution of larger mineral grains as weathering progresses, as well as to the addition of eolian fines.

Dissolution of sand-size quartz, feldspars and biotite appears to be the dominant chemical weathering process on the nunatak. Evidence of this is seen in the widespread development of etch features on the surface of feldspar grains and along the edges of biotite grains. The rounding of mineral grains in the upper parts of the profiles as seen under the SEM and reflected in the Riley Inscribed Sphericity Index further supports the importance of mineral grain dissolution. These processes are reflected in the generally lower molar ratios of alkali earths, alkalis and total bases:resistates observed in the grus and soil compared to the associated bedrock.

Some evidence of iron oxidation in ferromagnesian minerals is also apparent. This is reflected in the increase in the iron: alumina ratio in some of the grus and soil samples and by visual observation, although no evidence was found from SEM observations.

Secondary clay mineral formation appears to be limited to the fine-grained fractions of the grus and soil. Specifically, biotite is the primary mineral being affected by clay formation with extensive alteration to vermiculite. Formation of the vermiculite is apparently the result of the loss of potassium and magnesium from interlayer positions within the biotite with associated oxidation of iron.

Grain size, geochemical data, and scanning electron microscope evidence strongly attest to the importance of eolian processes in addition to weathering processes. Eolian additions and concentrations exert a strong influence on the extent to which the effects of chemical weathering are able to be expressed in grus and soil profiles.

Chemical weathering clearly occurs in the periglacial environment of the Vantage Peak nunatak. The processes operating are similar to those reported from other climatic environments, although in this locality dissolution appears to be the dominant process while clay formation is inhibited. This may be a function of climate, or it may simply be a reflection of the length of time since exposure of the nunatak from beneath glacial ice.

Acknowledgments: The authors acknowledge the field support provided by M.M. Miller and the Foundation for Glacier Research to Colin Thorn, without which this research would not have been possible. Also, a Faculty Research Incentive Grant to John C. Dixon from the J. William Fulbright College of Arts and Sciences, University of Arkansas, made much of the laboratory work possible. The electron microscope work was done at the Center for Electron Microscopy of the University of Illinois. Grain-size analysis and X-ray diffractometry were carried out in the Department of Agronomy at the University of Arkansas.

#### BIBLIOGRAPHY

Birkeland, P.W. (1969) Quaternary paleoclimatic implications of soil clay mineral distribution in a Sierra Nevada-Great Basin transect. J. Geol., Vol. 77, 289-302.

(1984) Soils and Geomorphology. New York: Oxford.

and Janda, R.J. (1971) Clay mineralogy of soil development from Quaternary deposits of the eastern Sierra Nevada, California. *Geol. Soc. Amer. Bull.*, Vol. 82, 2495-2512.

Burns, S.F. and Tonkin, P.J. (1982) Soil geomorphic models and the spatial distribu-

tion and development of alpine soils. In: C.E. Thorn (ed.), Space and Time in Geomorphology, pp. 25-43. London: George Allen and Unwin.

- Caine, T.N. (1979) Rock weathering rates at the soil surface in an alpine environment. *Catena*, Vol. 6, 131-144.
- Colman, S.M. (1982) Chemical weathering of basalts and andesites: Evidence from weathering rinds. U.S. Geol. Survey Prof. Paper 1246.
- Day, P.R., Von Bauel, C.H.M., Jamison, V.C., Kohnke, H., Lutz, J.F., Miller, R.D., Page, J.B., and Peele, T.C. (1956) Report of the committee on physical analyses. Soil Science Soc. America, Vol. 20, 167-169.
- Dixon, J.C. (1983) Chemical weathering of Late Quaternary cirque deposits in the Colorado Front Range. PhD thesis, University of Colorado, Boulder.
- Douglas, L.A. (1977) Vermiculites. In: J.B. Dixon and S.B. Weed (eds.), Minerals in Soil Environments, pp. 259-292. Soil Sci. Soc. America.
- Ellis, S. (1980) An investigation of weathering in some arctic-alpine soils on the flank of Oksskolten, north Norway. *Jour. Soil Soc.*, Vol. 31, 372-282.
- Embleton, C. and Thornes, J. (1979) *Process in Geomorphology*. New York: John Wiley and Sons.
- Fahey, B.D. (1983) Frost action and hydration as rock weathering mechanisms on schist: A laboratory study. *Earth Surface Processes and Landforms*, Vol. 8, 535-545.
- Gilky, A.K. (1958) Geological structures in the Camp Ten nunatak, Juneau Icefield Alaska. The Foundation for Glacier Research Special Report No. 4. Seattle, WA.
- Grim, R.E. (1968) Clay Mineralogy. New York: McGraw-Hill.
- Hall, K. (1980) Freeze-thaw activity at a nivation site in northern Norway. Arctic and Alpine Research, Vol. 12, 183-194.
- Hudec, P.P. (1973) Weathering of rocks in arctic and subarctic environments. In: J.D. Aitken and D.J. Glass (eds.), *Proceedings of the Symposium on the Canadian Arctic*, pp. 313-335. University of Waterloo, Waterloo: Geological Society of Canada.
- Isherwood, D. and Street, A. (1976) Biotite-induced grussification of the Boulder Creek granodiorite, Boulder County, Colorado. Geol. Soc. America Bull., Vol. 87, 266-270.
- Krinsley, D.G. and Doornkamp, J.C. (1973) Atlas of Quartz Sand Surface Textures. Cambridge University Press.
- Mahaney, W.C. (1974) Soil stratigraphy and genesis of neoglacial deposits in the Arapaho and Henderson Cirques, Central Colorado Front Range. In: W.C. Mahaney (ed.), Quaternary Environments. Toronto Geo. Mon., 5, 197-240.
- McGreevy, J.P. (1981) Some perspectives on frost shattering. *Progress in Physical Geography*, Vol. 5, 56-75.
- Miller, M.M. (1976) Quaternary erosional and stratigraphic sequences in the Alaska-Canada Boundary Range. In: W.C. Mahaney (ed.), Quaternary Stratigraphy of North America, pp. 463-492. Stroudsburg, PA: Dowden, Hutchison and Ross.
- Péwé, T.L. (1951) An observation on wind-blown silt. Jour. Geol., Vol. 59, 399-401.
- Rapp, A. (1960) Recent development of mountain slopes in Karkevage and surroundings northern Norway. Geografiska Annaler A, Vol. 52, 169-200.
- Reynolds, R.C., Jr. and Johnson, N.M. (1972) Chemical weathering in the temperate glacial environment of the northern Cascade Mountains. *Geochim. et Cosmochim.*, *Acta*, Vol. 36, 527-554.

130

Rieger, S. and Juve, R.L. (1961) Soil development in recent loess in the Matanuska Valley, Alaska. Soil Sci. Soc. Amer. Proc., Vol. 25, 243-248.

Riley, N.A. (1941) Projection sphericity. Jour. Sed. Pet., Vol. 11, 94-97.

- Shroba, R.R. (1977) Soil development on Quaternary tills, rock glacier deposits and taluses, southern and central Rocky Mountains. PhD thesis, University of Colorado, Boulder.
- Soil Survey Staff (1972) Soil survey laboratory methods and procedures for collecting soil samples. Soil Survey Investigations Report No. 1, SCS. USDA, U.S. Govt. Printing Office, Washington, DC.

Swineford, A. and Fry, J.C. (1945) A mechanical analysis of windblown dust compared with analyses of loess. *American Jour. Sci.*, Vol. 243, 249-255.

Tamm. O. (1924) Experimental studies on chemical process in the formation of glacial clay. Sverig. Geol. Unders. Arsbook, Col. 18.

Thorn, C.E. (1976) Quantitative evaluation of nivation in the Colorado Front Range. Geol. Soc. Amer. Bull., Vol. 87, 1169-1178.

\_\_\_\_\_ (1979) Bedrock freeze-thaw weathering regime in the alpine environment. *Earth Surface Processes*, Vol. 4, 211-228.

\_\_\_\_\_ and Darmody, R.G. (1980) Contemporary eolian sediments in the alpine zone, Colorado Front Range. *Physical Geog.*, Vol. 1, 162-171.

\_\_\_\_\_ and Hall, K. (1980) Nivation: an arctic-alpine comparison and reappraisal. Jour. Glaciology, Vol. 25, 109-124.

- White, S.E. (1976) Is frost action really only hydration shattering? A review. Arctic and Alpine Research, Vol. 8, 1-6.
- Williams, J.E. (1949) Chemical weathering at low temperatures. *Geog. Rev.*, Vol. 39, 129-135.