CLAY MINERAL FORMATION IN AN ALPINE ENVIRONMENT

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Abstract – Vermiculite, mixed-layer vermiculite–phlogopite, and smectite are presently forming from igneous and metamorphic bedrock in the alpine zone of the northern Cascades, Washington. In addition, south-facing exposures of quartz-diorites and metadiorites above snow line are weathering to ferruginous bauxite. Calculations indicate that vermiculite is presently forming from phlogopite schists in this environment at a unit area rate that is approximately six times the average estimated rate of clay erosion for North America. The mineralogical data indicate that chemical weathering in this region is a quantitatively significant process, and suggest that in the development of current geomorphic concepts researchers may have generally underestimated the importance of chemical weathering in alpine environments.

INTRODUCTION

FIELD STUDIES and sampling traverses were conducted in the vicinity of South Cascade Glacier (Dome Peak $7\frac{1}{2}$ min. Quadrangle, 1963) in northwestern Washington. The region is the site of a continuing hydrologic study by the United States Geological Survey and has been well described in numerous publications (Meier and Tangborn, 1965; Tangborn, 1966; Miller, 1969). The glacier has an average altitude of 1970 m, regional snow line is at 1825 meters, and the local peaks reach altitudes of up to 2520 m. Total precipitation for 1958–1964 averaged 384 cm water equivalent and was 80 percent winter snow; runoff is nearly balanced by precipitation and evaporation is minimal (Meier and Tangborn, 1965).

The regions adjacent to South Cascade Glacier support numerous hanging glaciers, several of which discharge rock flour into small terminal lakes. Slope wash also contributes sediment to these and South Cascade Lake. Megascopic biological activity above snow line is minimal and thus is not significantly involved in weathering and in soil-forming processes.

Local bedrock types in the area studied include (1) migmatite consisting of phlogopite–actinolite schists, locally quartzose, intruded by granitic rocks in lit-par-lit structures; (2) older quartz diorite that has been metamorphosed into a greenstone; (3) younger, unmetamorphosed South Cascade quartz diorite; and (4) abundant but thin late tectonic basaltic and lamprophyric dikes.

PROCEDURES

Samples of lithosols were collected from peak summits, ridges, and slopes; bottom sediment samples were obtained from glacial streams and lakes. Altogether 120 samples were collected and studied over a 4-yr period. The results given in detail here for a few samples are representative of the sample suite. Table 1 provides data on the locations and aspects of the samples.

In the laboratory, samples were dispersed in deionized water and separated by settling into the $> 20\mu$, $2–20\mu$, and $< 2\mu$ fractions (e.s.d.). Bedrock (BR) samples were ground and the $2–20\mu$ fractions isolated for X-ray studies. All suspensions of the $2–20\mu$ fractions were magnesium saturated. 150 ml of $0.1M$ $MgCl_2$ was added to approximately 500 mg of solid and the suspension was agitated for 15 min in an automatic sample shaker. The suspension was centrifuged and the supernatant discarded. This procedure was repeated four times followed by washing for five similar cycles with deionized water. An aliquot of the suspension was mixed with $\frac{1}{3}$ its volume of a solution containing 70% ethanol and 30% glycerine. The suspension was centrifuged onto a porous plate according to the method of Kinter and Diamond (1956). A porous plate was also made without glycerine from the magnesium-saturated suspension. Porous plate samples were allowed to air dry for 24 hr in laboratory air. Samples which were magnesium-saturated but not glycerol-solvated were heated at 550°C for one hour, allowed to cool, and stored in contact with laboratory air. Humidity measurements of laboratory air were made twice daily over the period of the X-ray work, and values were obtained that varied between 15 and 30% relative humidity. Measurements were performed with a Bendix Model 566 Psychrometer.

For sample LS-1, (see Fig. 1), the $< 2\mu$ fraction

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Table 1. Description of samples

Sample	Location	Aspect	Remarks
BR-1	West wall, South Cascade Glacier	NE-Slope*	Phlogopite–actinolite schist
BR-2	Talus; Lizzard Mtn.	N-Slope	Phlogopite–actinolite schist
BR-3	Lizzard Mtn.	N-Slope	Phlogopite–actinolite schist
BR-4	Talus; LeConte Mtn.	SW-Slope	Metadiorite
BR-5	Dome Peak	S-Slope	Biotite–quartz–diorite
LS-1	West wall, South Cascade Glacier	NE-Slope	Assoc. with BR-1
LS-2	Sentinal Peak	SW-Slope	Assoc. with quartz-rich phase of schist
LS-3	Sentinal Peak	SW-Slope	Assoc. with quartz-rich phase of schist
LS-4	Lizzard Mtn.	N-Slope	Assoc. with BR-3
LS-5	LeConte Mtn.	SW-Slope; Summit	Assoc. with metadiorite
LS-6	Dome Peak	S-Slope; Summit	Assoc. with BR-5
LS-7	Col; W. End White Rock Lakes	Crest	Assoc. with quartz–diorite–schist contact
LK-1	LeConte Lake	At tree line	Bottom sediment
LK-2	South Cascade Lake	At tree line	Bottom sediment
LK-3	White Rock Lake	At tree line	Bottom sediment
LK-4	3500′ W of SW corner South Cascade Lake	Pond on N-Slope above tree line	Bottom sediment

*NE-facing slope.

was isolated and studied. One portion was analyzed in an untreated condition, another was treated only with glycerol, another was treated as described above, and a final portion was potassium saturated according to procedures similar to those described for the magnesium treatment except that 1M KCl was used. The potassium-saturated material was not treated with glycerol, and was oven dried at 110°C; the others were allowed to air dry. For all specimens of LS-1, ($< 2\mu$) suspensions were pipetted onto glass slides and dried in order to produce slides for X-ray diffraction studies.

The smectite sample shown on Fig. 5 is $< 2\mu$ material. A suspension was pipetted onto a glass slide, dried at 90°C, and solvated by flooding with a mixture containing equal portions of ethanol and ethylene glycol. The excess liquid was blotted off and the slide was allowed to air dry.

X-ray diffractograms were recorded over the angular range $2\theta = 2$ to $2\theta = 35°$ utilizing a General Electric XRD-5 Diffractometer equipped with a copper anode tube. Scale factors were varied between 10,000 c/s and 2000 c/s full scale deflection in order to adjust intensities so that none were off-scale. J. Hower kindly carried out several

chemical analyses by X-ray fluorescence methods which are described by Czamanske, Hower, and Millard (1966). The data are listed in Table 2.

CRITERIA FOR MINERAL IDENTIFICATION

Mixed-layer vermiculite-mica is best developed in sample LS-1 (Figs. 1–3). Its relative abundance is greater in the $< 2\mu$ than in the $2–20\mu$ fractions, hence detailed X-ray studies were made of the $< 2\mu$ fraction of LS-1 and these are shown by Fig. 1. The interstratified phase is characterized by a long-spacing ($d \simeq 26$ Å) and an essentially rational series of higher orders. Reflections occur at spacings of 26, 12·2, 4·92, 3·49, and 2·71 Å. These are underlined on Trace (a), Fig. 1*, and they apparently are the (001), (002), (005), (007), and (009) reflections from an approximately 24·4 Å periodicity. This fundamental spacing suggests the interstratification of 10 and 14·4 Å components, and the essential rationality of the higher "orders" indicates that the

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*The discontinuity in intensity on Trace (a) of Fig. 1 and on the traces of Fig. 2 was caused by a change in scale factor from 2000 c/s to 5000 c/s below 11°2θ.
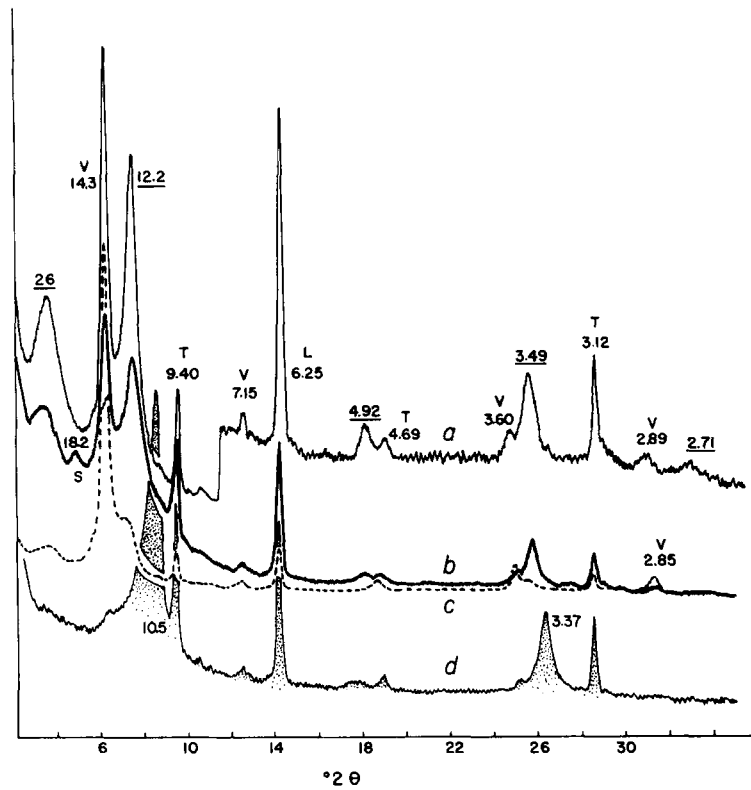
Fig. 1. X-ray diffraction study of sample LS-1, < 2μ. Trace (a) untreated; (b) glycerol-solvated; (c) magnesium-saturated and glycerol-solvated; (d) potassium-saturated and dried at 110°C.
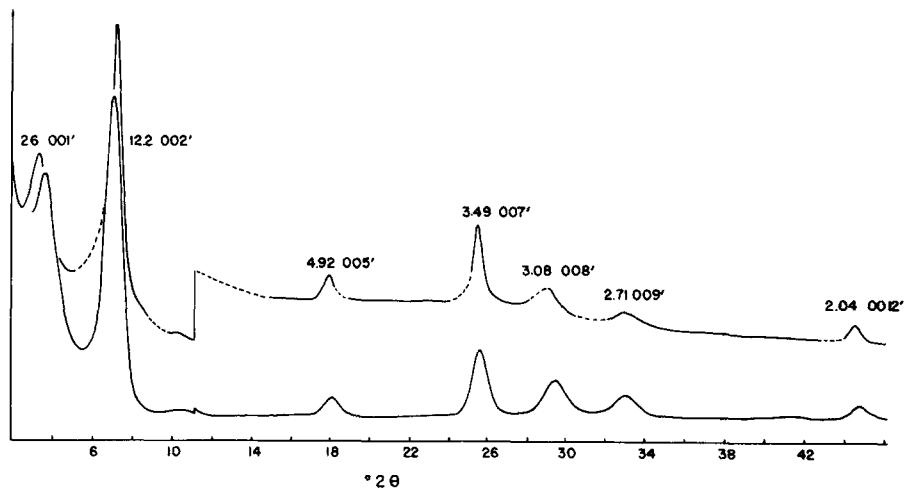

Fig. 2. Comparison between observed (top trace) and computed diffraction profile for mixed-layered phase in LS-1, < 2μ.
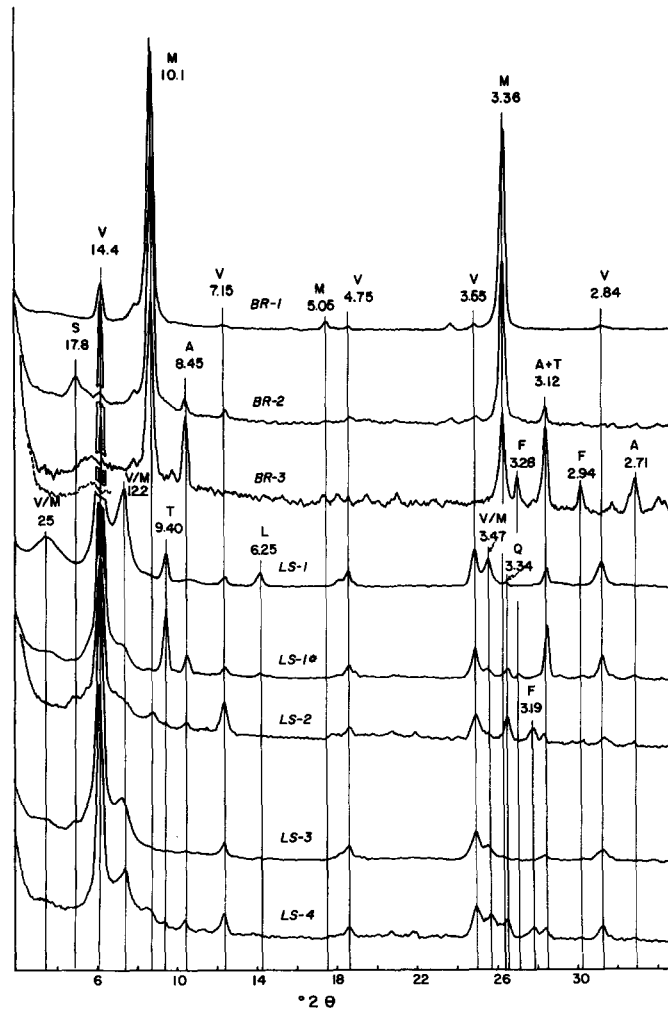
Fig. 3. X-ray diffraction patterns of micaceous bedrock and associated lithosols. In this and subsequent figures, the following abbreviations are used: vermiculite (V), mica (M), smectite (S), amphibole (A), talc (T), mixed-layer vermiculite–mica (V/M), feldspar (F), lepidocrocite (L), quartz (Q), chlorite (C), and gibbsite (G).

Table 2. Chemical analyses of bauxitic lithosols, $< 2\mu$
(Per cent)

	Summit E. Peak LeConte Mtn.	LS-5	W. End LeConte Ridge	LS-7
SiO_2	20·90	10·98	18·00	21·57
Al_2O_3	29·13	46·11	23·08	26·89
ΣFe as Fe_2O_3	4·39	2·85	5·88	5·44
MgO	0·45	0·38	0·43	0·16
CaO	2·31	2·86	3·00	9·69
K_2O	0·56	0·43	0·49	0·21
Na_2O	0·21	0·19	0·18	0·22
TiO_2	0·50	0·47	0·36	0·76
Loss on ignition	41·3	35·2	48·1	33·1
	99·8	99·5	99·5	98·0

interstratification is non-random, involving here the regular alternation of 10 and 14·4 Å unit layers.

Trace (a) on Fig. 1 was obtained from air-dried material, and Trace (b) from glycerol-solvated clay. The nature of the diffraction phenomena from the interstratified material is similar between the two, indicating that smectite is not a component of the interstratification. Trace (d) was obtained from potassium-saturated, oven-dried clay, and it shows the absence of reflections from the mixed-layered phase; instead, the pattern is dominated by a 10 Å periodicity. Note also on Fig. 7 (LS-1) that the $2-20\mu$ fraction of this same sample shows complete collapse to 10 Å upon heating to 550°C. These results indicate that the larger spacing in the interstratified complex is vermiculite and not chlorite. The 10 Å portion is unaffected by potassium solvation or by heating, as would be anticipated. The mineral is thus a regularly interstratified vermiculite-mica. Trace (c) on Fig. 1 shows that magnesium saturation markedly diminishes the amount of vermiculite–mica in the sample, indicating that potassium in the mica layers is quite easily replaced.

A more detailed description of the nature of the interlayered phase was developed by computer simulation techniques. The simulation was accomplished by a modification of the MacEwan Fourier Transform Method (MacEwan, 1958), and the computed diffraction profile (Fig. 2) includes the effects of a random powder Lorentz-polarization factor, the low angle intensity loss caused by a 1° beam divergence in conjunction with a sample 4 cm long, and a summation of the effects of a distribution of crystallite thicknesses. These methods have been described by Reynolds (1967) and Reynolds and Hower (1970). Atomic coordinates and atomic temperature factors for the silicate skeleton, and the details of structure and composition of the vermiculite interlamellar region, were taken as identical to those described for Kenya vermiculite by Mathieson and Walker (1954).

Figure 2 shows a comparison between the calculated and observed diffraction profiles for sample LS-1, $< 2\mu$. The X-ray diffraction pattern (top trace) is the same as Trace (a), Fig. 1, except that here it has been smoothed and peaks due to other minerals have been removed (dashed portions). The calculated profile is based on an interstratified vermiculite–phlogopite which contains (1) 0·30 Fe atoms/3 octahedral positions, (2) 0·9 K atoms/ Si_4O_{10} mica unit, (3) 50 per cent vermiculite, (4) a stacking sequence in which the probability of a vermiculite layer succeeding a vermiculite layer is 0·15, i.e. the interstratification is ordered in a sequence of near perfect alternation of phlogopite and vermiculite units, and (5) equal portions of crys-

tallites containing 7, 8, 9, and 10 unit-layers per crystallite.

Agreement between the two profiles is sufficiently good so as to verify the essential validity of the assumed structure. Relative intensities of reflections through the $(0012)'$ (the prime designation is used here to denote a superlattice reflection) agree very well between observed and calculated profiles. Peak positions are similar between the two profiles, except for the $(001)'$ and $(002)'$. The error in the $(002)'$ is slight ($\sim 0·15°2\theta$) and the displacement of the $(001)'$ is probably due to particle size effects (see Reynolds 1968). A slight reduction in assumed mean crystallite thickness causes a significant increase in apparent d in this region of the diffraction profile. The structural interpretation could doubtless be refined, but the structure is defined sufficiently for the purposes of this work. The analysis shows that the interstratified phase in sample LS-1 (and probably in other lithosols and sediments as well) is a ferroan phlogopite-vermiculite containing essentially equal proportions of phlogopite and vermiculite in regular, alternating array. The structure is a trioctahedral analog of allevardite (Brindley, 1956).

Vermiculite is the most common secondary phase in the clay and silt size fractions of the lithosols and sediments studied here (Figs. 1, 3, 4, 6). It is identified on the basis of, (1) a first order X-ray diffraction maximum at about 14·3 Å from material which has been magnesium-saturated and glycerol-solvated (Walker, 1958), and (2) a first order maximum whose intensity is much greater than that of any of the other higher order reflections (Walker, 1961). Confirmatory evidence lies in the collapse of magnesium-saturated material to ~ 10 Å upon heating to 550°C (Fig. 7). Trioctahedral values were obtained from measurements of the spacings of the (060) reflections from several relatively pure samples (LS-1, LS-2, LS-4, LK-4).

Smectite is abundant in some of the lithosols. Figure 5 shows the diffraction pattern of the glycol-solvated $< 2\mu$ fraction of a lithosol collected from a lamprophyric dike. This same material not treated with glycol, but air dried, produced a diffraction pattern characterized by a high intensity peak approximately at 15 Å. The value for the (060) (Fig. 5) indicates that it is trioctahedral. No classification beyond this point is attempted, hence the mineral is described as a trioctahedral smectite.

Small amounts of unspecified smectite occur in other lithosols. A weak maximum at $\sim 18·0$ Å occurs in some magnesium-saturated, glycerol-solvated samples, yet is absent from samples which were not glycerol solvated. Examples of small but detectable concentrations of smectite can be seen

in Fig. 1, Trace (b), and in Fig. 3, samples BR-2, LS-2, and LS-3.

Gibbsite was identified on the basis of a strong reflection at 4·83 Å, and a weaker one at 4·35 Å. Heating the sample at 250°C for one hour caused the elimination of both peaks. An example of gibbsite in a lithosol is shown by Fig. 4, sample LS-5.

Lepidocrocite was identified by a single strong reflection at 6·25 Å which was eliminated by heating the sample at 250°C for 1 hr. Sample LS-1, < 2µ (Fig. 1) shows an example of a lepidocrocite-containing lithosol.

Chlorite is ubiquitous, though rarely abundant in the lithosols and sediments studied here. Its presence is indicated in samples which show fairly intense peaks at positions near the vermiculite (002), (003), and (004) diffraction maxima. Confirmatory information was obtained by heating the

magnesium-treated samples at 550°C for 1 hr. The appearance of a significant 10 Å reflection is taken as evidence of vermiculite, and the presence of chlorite is revealed by the retention of a peak at about 14 Å, coupled with a large intensity reduction of the second-order peak at 7·15 Å. Comparison of the air dried with the heat-treated samples (Fig. 7) shows that for most of the LK (lake) and LS (lithosol) samples described here, the original diffraction peak at 14 Å is due mostly to vermiculite. It should be noted that for many samples, chlorite interference is significant on vermiculite orders higher than the (001). Chlorite is believed to be detrital in the sediments and lithosols, for it is abundant in the metadiorite bedrock of this region.

Kaolinite is not listed as a component in any of the lithosols or sediments described here, yet its presence cannot be certainly ruled out by the analytical techniques employed in this study.
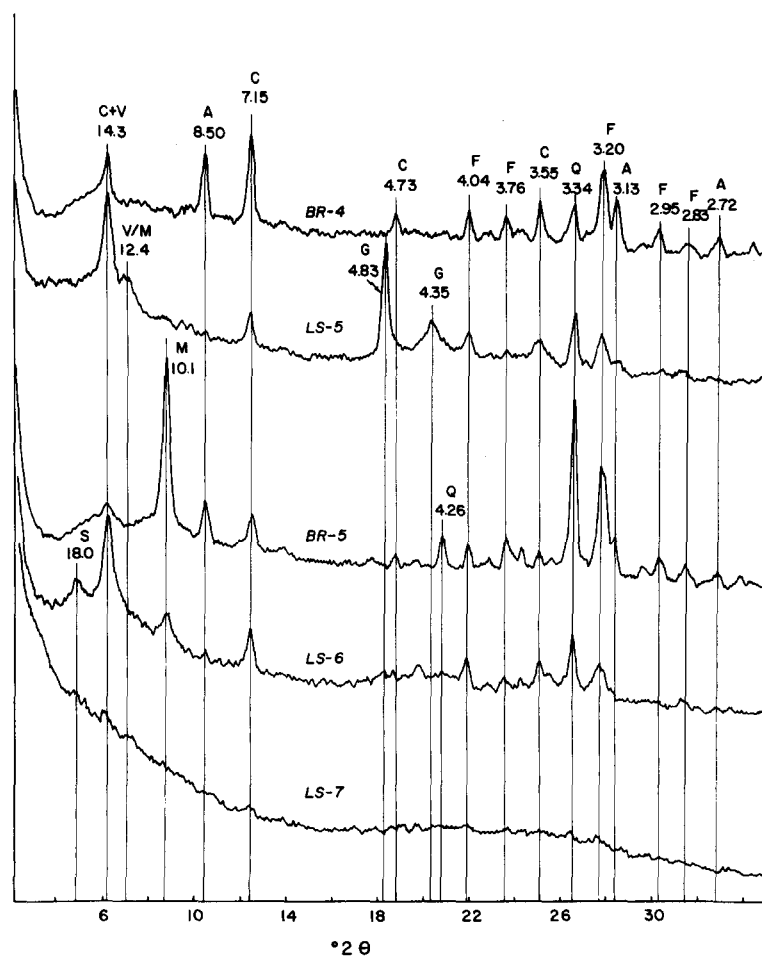

Fig. 4. X-ray diffraction patterns of metadiorite and quartz diorite, with associated lithosols.

However, all samples which show a peak at 4·73 Å also show a significant one at 3·55 Å. Because kaolinite has no reflection at 3·55 Å, the 4·73 Å peak is best referred to chlorite. Kaolinite may be present, but the above consideration indicates that it is not abundant in any sample.

Other primary minerals, such as mica, talc, amphibole (actinolite), quartz and feldspar were identified on the basis of their published diffraction patterns. Their presence was also verified by a study of twelve thin sections of the various bedrock types found in the South Cascade Glacier watershed.

MINERALOGICAL AND CHEMICAL COMPOSITION

Figure 3 shows X-ray diffraction patterns for three samples of phlogopite–actinolite schist (BR-1, 2, and 3) and four samples of lithosols developed on these lithologies. All X-ray specimens are 2–20μ equivalent spherical diameter, except for Sample LS-1* which is 0·25–0·84 mm. Comparisons among the various traces of Fig. 1 with LS-1 and LS-1* of Fig. 3 provide data on the $< 2\mu$, 2–20μ and 2500–8400μ size fractions respectively for this sample. The dashed trace for the region $< 6°2\theta$ which appears under trace BR-3 was obtained from a clean porous plate, indicating that a similar profile for BR-3 does not necessarily denote poorly crystalline vermiculite in that sample.

The patterns of Fig. 3 show that the three samples of bedrock, BR-1, BR-2, and BR-3 consist predominantly of mica. The very low intensities of the (002) reflections for all three samples indicate that the mica is trioctahedral and this was verified by thin section studies of the three samples in which the mica showed marked pleochroism. Application of the method of Gower (1957) indicated, for sample BR-1, that the mica contains 0·6 Fe atoms/3 octahedral positions. Thus it is classified as a ferroan phlogopite (Deer, Howie and Zussman, p. 42, 1962).

The lithosol samples shown by Fig. 3 consist predominantly of vermiculite, with small amounts of interstratified vermiculite-mica and/or smectite. Vermiculite is the most abundant mineral in all size fractions, and even coarse sand separates and bulk lithosols in the field are rich in megascopically identifiable vermiculite. Lepidocrocite is abundant in the $< 2\mu$ fraction of LS-1 (Fig. 1), but diminishes in concentration in the coarser size fractions (Fig. 3). It is not present in detectable concentrations in any of the bedrock samples. Quartz, feldspar, talc, and actinolite occur in small amounts in some samples of bedrock and in some associated lithosols. These minerals are primary phases which have apparently persisted through the chemical weathering processes that have developed the lithosols.

But the most important observation is the sharp contrast between the micaceous bedrock and the vermiculitic lithsols. These data leave little doubt that, for these samples, vermiculite has formed pedogenically from phlogopite. Smaller amounts of mixed-layer vermiculite–mica and lepidocrocite have been produced during the weathering process.

Figure 4 shows examples of bauxitic lithosols developed on metadiorite and biotite-quartz diorite. LS-5 is a lithosol developed on metadiorite lithology (BR-4), and it shows significant amounts of vermiculite and gibbsite, none of which are in evidence in the parent lithology (BR-4). On the other hand, the lithosol is deficient in chlorite, amphibole and feldspar, all of which are abundant in the parent lithology. Apparently, these primary minerals are transformed to vermiculite and gibbsite by the local weathering processes. In addition, amorphous material is produced, as indicated by the weak diffraction pattern of LS-5, the scattering hump between 16° and 30°2θ, and the amorphous character of a similar material (LS-7). Sample BR-5 is from biotite–quartz diorite, and LS-6 is its associated lithosol. Again, the pattern is similar to that of LS-5 except that small amounts of smectite are present and gibbsite is absent. Sample LS-7 is from the B horizon of a zoned soil developed on a high col which is underlain by quartz diorite and migmatite. Presumably its topographic situation prevented erosion and allowed its accumulation and zonal development. It may be a paleosol.

Chemical analyses of the $< 2\mu$ fractions of LS-5 and LS-7 are shown by Table 2, together with analyses of two other lithosols developed on metadiorite lithology. All are sufficiently high in Al_2O_3/SiO_2 to be classified as bauxites. The samples shown in Table 2 were calcium-saturated, prior to analysis, and apparently the last sample in the table was insufficiently washed; hence, the calcium for all are suspect. On the other hand, the very high ratios of iron to magnesium are significant and are consistent with the bauxitic character of the samples. No chemical data are available for the bedrocks, but published data on diorites and quartz diorites show that these rocks never attain aluminum/silicon or iron/magnesium ratios as high as those found in the lithosols. Volcanic ash does not approach compositions similar to those of the lithosols, so ashfall in the watershed has not produced the bauxitic lithosols. The data are best interpreted by assuming that local weathering conditions have produced lithosols of bauxitic composition from metadiorite and quartz diorite. Small amounts of residual vermiculite and smectite are consistent with this interpretation (Jackson, 1956, p. 179).

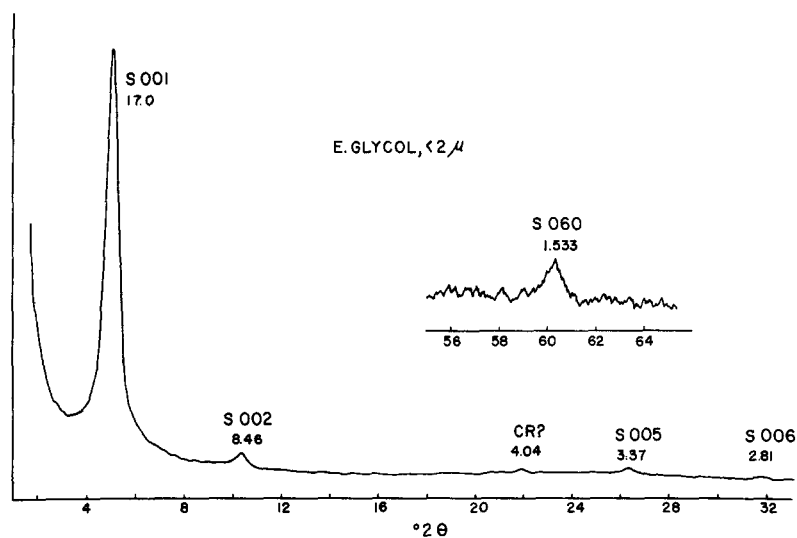Figure 5 shows an example of a trioctahedral

Fig. 5. X-ray diffraction pattern of smectite ($< 2\mu$) from lithosol developed on lamprophyric dike. CR(?) refers to the possible presence of cristobalite.

smectite from weathered material on a lamprophyre dike. The trioctahedral composition of this mineral is consistent with a genesis from a ferromagnesian igneous parent rock. The abundance of smectite in this sample could be attributed to volcanic ash fall in the watershed, but this hypothesis fails to explain the virtual absence of smectite in lithosols developed on the other rock types in the area. The smectite has doubtlessly been formed by the chemical weathering of the underlying lamprophyric dike rock.

Figure 6 shows four diffractograms of bottom sediments collected from local glacial lakes. The minerals identified in the lithosols described by the previous figures should be anticipated in the lake sediments because transport mixes the various sediments derived from all parts of the drainage basin. However, only the pedogenic minerals vermiculite and vermiculite-mica are present in significant amounts in addition to detrital minerals. Presumably the dominance of these minerals can be explained by, (1) the small area of exposed lamprophyres and basalts in the watershed, (2) the difficulty of detecting amorphous material when it is mixed with crystalline phases, and (3) the relatively high rate of transformation of phlogopite to vermiculite in this weathering regime, which causes vermiculite to be the dominant pedogenic phase in the entire watershed.

A more detailed examination of the mineralogy of the lake sediments shows that each is influenced by the bedrock and/or the local climate in its watershed. LK-1 is from LeConte Lake which receives drainage from the LeConte Glacier watershed.

Here the bedrock is entirely metadiorite and, unlike South Cascade Glacier, the local drainage basin is occupied by an active hanging glacier on a precipitous and cold north face. LK-1 is rich in chlorite, presumably inherited from the metadiorite, and shows no definite pedogenic phases. The X-ray diffractogram of the heat-treated aliquot of this sample (Fig. 7) indicates the presence of abundant chlorite, and little or no vermiculite. The chlorite-rich bedrock and the vigorous scour of the hanging glacier have apparently swamped LeConte Lake with mechanical weathering debris, and little or no chemical weathering products are in evidence. Sample LK-2 is from South Cascade Lake, and the drainage here involves all of the rock types described earlier. South Cascade Glacier, which drains into the lake, is a stagnant valley glacier and is flanked on one side by south and southwest facing cliffs. These receive large amounts of solar energy which can drive chemical weathering processes, and this, plus the occurrence of phlogopite schist in the drainage area, and the relatively small mechanical load contributed by South Cascade Glacier, produced a sediment richer in vermiculite than LK-1. Samples LK-3 and LK-4 are sediments from local basins in which the major rock type is phlogopite-containing migmatite. Glacial scour produced important contributions to LK-3, and is not involved in the formation of LK-4; slope wash contributed the bulk of sedimentary debris to the latter. Both samples show the important effect of local bedrock which, for these two sediments, has produced a mineral composition that is dominated by vermiculite.
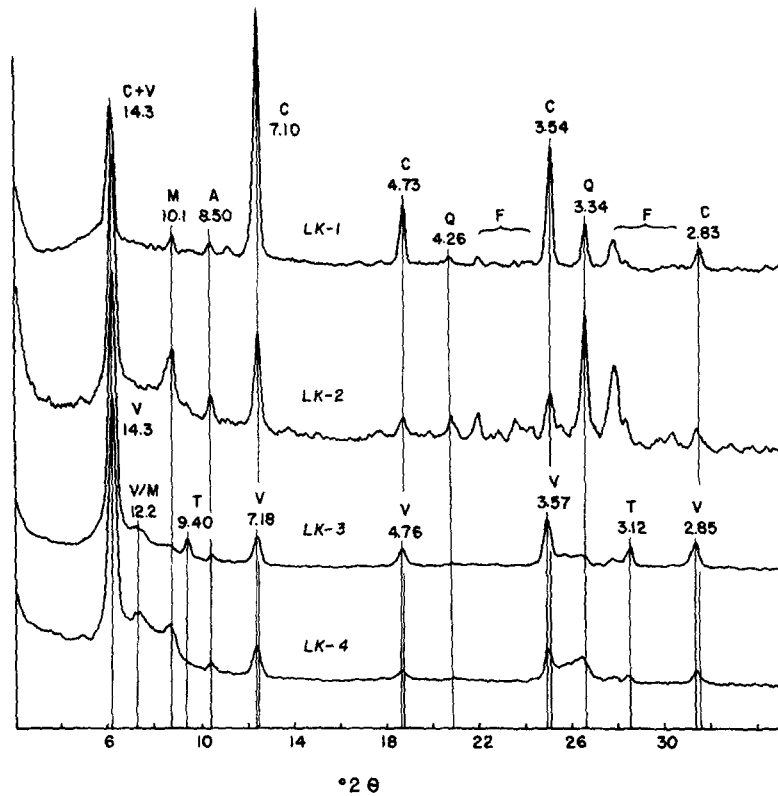
Fig. 6. X-ray diffraction patterns of lake sediments.

DISCUSSION OF CHEMICAL WEATHERING

The preceding discussion of the mineralogy of bedrock, lithosols, and lake sediments shows that each lithosol contains a pedogenic mineral assemblage that is appropriately related to the primary mineralogy of the associated bedrock. Lake sediments contain mineral abundances that are related to local climate, bedrock type, and rigor of glacial scour in the drainage areas. Evidence is conspicuously absent that could provide serious support to suppositions that, (1) lithosols and sediments are merely mechanically comminuted bedrock, or (2) characteristic lithosol minerals such as vermiculite, vermiculite–mica, gibbsite, ledidocrocite and smectite are due in large part to accumulations of volcanic ash or other airborn detritus. The observed distribution of lithosol and sediment types could only have come about by the pedogenic development of lithosol minerals from underlying bedrock, and their subsequent transportation by fluvial and/or glacial processes.

The clay minerals in the South Cascade Glacier area have formed from associated bedrock minerals, but a possibility exists that these clays are relicts from weathering processes that took place during an older and more mild climatic regime. Miller (1969) has studied the moraines of South Cascade and other glaciers in the region by methods of radiocarbon dating, dendrochronology, and lichenometry. His observations suggest that glaciers in this area have been in general retreat for the past 800 yr. It appears that there has been no extended period of mild climate during this period. An hypothesis of an ancient origin for the local clays requires that relict lithosols have persisted here for approximately 800 yr, and persisted in sufficient quantities so that they are the principal constituents of the present particulate matter in the area.

Except for the southwest face of LeConte Mountain, which makes up about $\frac{1}{3}$ of the mountain face area surrounding South Cascade Glacier, the slopes consist of either freshly glaciated rock surfaces or permanent snowfields and hanging tributary glaciers. Slopes are steep, ranging between 30° and 55°, with appreciable areas approaching the vertical. The bare rock faces are flushed with melt water during the spring and are scoured yearly by snow avalanches. Presumably, the tributary glaciers are actively scouring their beds. Rock falls are frequent from summit areas; these remove old
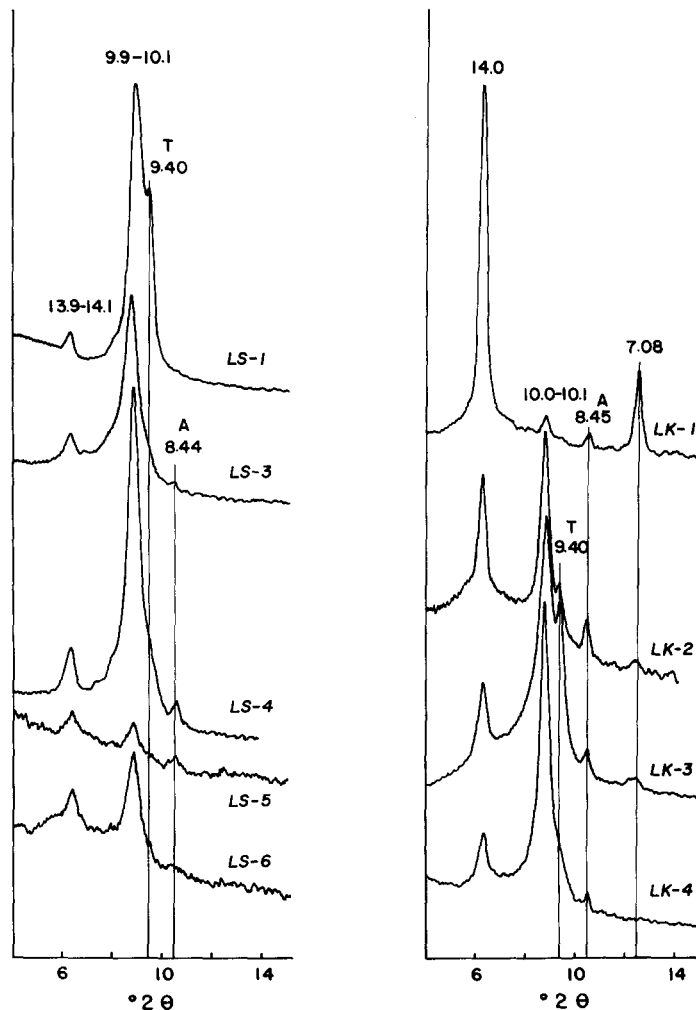
Fig. 7. Low angle X-ray diffraction patterns of heat-treated (550°C) lithosols and lake sediments.

surfaces from the higher altitudes of the watershed. Given such conditions, it is likely that the residence times of particles on the slopes are short. The age of debris may be measured in years or perhaps decades, but it seems unlikely that significant amounts of material could persist on such slopes for centuries.

It might be argued that slope debris consists of transported old lithosolic material from the summit areas. Along the west and south rim of the glacier, the arete crest is from a few inches to a few feet wide, and slopes drop off steeply on either side. The thickness of lithosols on the crest is a few inches at best. Hence, available source material appears to be too limited to have contributed significantly to the lithosols on the mountain slopes. On the east side of the glacier, Sentinal Peak makes up

the summit region. Its higher portions are composed of scree and talus, and its limited summit area, mantled with a few inches of lithosol, is too small to have contributed significant amounts of debris to its lower slopes and to South Cascade Glacier.

The bauxitic lithosols from the metadiorite of LeConte Mountain occur in a quite different climatic situation. The middle slopes of LeConte Mountain support some heather and have no large snow fields. These conditions occur in response to the intense solar radiation that LeConte receives because of its south west-facing slope. Perhaps paleosols could persist on these middle slopes. The summit area of the LeConte ridge, however, from which the bauxitic lithosols were collected, consists of near vertical cliffs, ravines, and pinnacles. Individual summit areas are 25–100 ft²; rock falls

are extremely common, and the base of the face supports the largest talus cones in the region. The two unlabelled lithosols of Table 2 were collected from the very tops of secondary summits of the LeConte massif. The summits here are tilted slopes of metadiorite on which are scattered a few patches of lithosol which measure a few inches on a side and approximately one inch deep. The rest of the surface is bare. Sample LS-5 was collected near the summit in a stone-fall gulley. Given the evidence of intense mechanical weathering and erosion, on these precipitous slopes, such samples cannot be very old, almost certainly not centuries old.

Based on the qualitative observations presented above, it is concluded that the lithosols in the vicinity of South Cascade Glacier have formed *in situ* under the influence of the present climatic regime.

Calculations of the rate of clay mineral formation are not apt to be highly accurate, but a reasonable estimate of vermiculite production can be made by considering the local cationic denudation rate for potassium. The weighted mean concentration of potassium in waters leaving the South Cascade Glacier watershed is $21\mu E/li$ (unpublished data in manuscript form). No significant amounts of potassium are found in precipitation and evaporative losses are minimal. Annual runoff is 384 cm, so the cationic denudation rate for potassium is $8\mu E$ K^+/cm^2/yr. Potash feldspar and phlogopite are the only potassium minerals in the region. The great stability of potash feldspar in a non-acid weathering regime indicates that the bulk of potassium leaving the region is derived from the transformation of phlogopite to vermiculite. Using a formula weight for vermiculite of 422, and assuming that 1 mole of potassium is liberated by the transformation of 1 mole of phlogopite to 1 mole of vermiculite, we obtain a value of $3\cdot4 \times 10^{-3}$ g of vermiculite produced per cm^2 of surface per year, or 34 metric tons/km^2/yr. This figure should be accurate within $\pm 10\%$ because of the simplicity and uniformity of the local mineralogy and because of the near-absence of complicating factors such as, (1) biological recycling of potassium, and (2) the formation of potassium-bearing secondary minerals.

The value of 34 T/km^2/yr is a minimum because the watershed does not consist of pure phlogopite. An unpublished map by Mark Meier, indicates that approximately $\frac{1}{3}$ of the watershed is underlain by phlogopite-bearing migmatite, hence the phlogopite–vermiculite transformation rate should be multiplied by three, and the value becomes 102 T/km^2/yr. No refined estimate is available of the average phlogopite content of the migmatite, but it is in the vicinity of 50% phlogopite. Therefore a final estimate for vermiculite formation lies in the region of 100–200 T/km^2/yr. For comparison purposes, the value 150 T/km^2/yr will be used.

Data listed by Garrels and McKenzie (1971) show that the average suspended load delivered to the oceans by the rivers of North America amounts to 86 metric tons/km^2/yr. Measured values for percent shale in the sedimentary lithosphere (summarized by Garrels and McKenzie, 1971, p. 206) indicate that the average sediment is approximately 50% shale, and Yaalon (1962) gives the average clay content of shales as 59%. Hence, the average amount of clay delivered to the oceans annually, for North America, is in the vicinity of 26 T/km^2/yr. It should be noted that much of this clay is doubtlessly recycled clay from sedimentary rocks, and does not all represent the annual increment of clay produced by pedogenic processes; therefore, even the value of 26 T/km^2/yr. is probably high for the production of clay by weathering. It is significant that the rate of vermiculite production in the South Cascade region is approximately six times the estimated total cyclic and non-cyclic production rate of clay in North America.

Any analysis of the sort developed above is subject to significant uncertainties. For example, it is assumed here that processes of clay formation and erosion have reached a steady state balance for North America, that is, clay is being eroded and transported to the sea as fast as it is being produced. Also, the composition of the average shale and indeed the fraction of shale in the sedimentary load may both differ between the average for the sedimentary lithosphere and the average for modern North American sediments. Despite these shortcomings, it seems reasonable to accept the conclusion that clay mineral formation in the alpine environment of the high Cascades is currently proceeding at a unit area rate that is greater than that estimated for North America as a whole.

Studies have been made and reported on the hydrochemistry of surface and glacial waters from the South Cascade region (Johnson, Reynolds and Campbell, 1970). The dominant anion in all waters studied is bicarbonate. The composition of waters of this type is usually controlled by bedrock weathering, rather than by evaporation or by precipitation (Gibbs, 1970). Quantitative interpretations of the data indicate that the total amounts of Ca, Mg, Na, and K removed annually per unit area from the South Cascade Glacier watershed are considerably larger than the overall world average. The high levels of contemporary chemical denudation, and the bicarbonate dominance in runoff waters support the evidences presented above for active chemical weathering and attendant clay mineral formation in this environment.

These findings have been anticipated in part by

earlier workers. Claridge's (1965) studies of Antarctic soils indicate that typical soil clays are forming there, although at reduced rates. Rainwater and Guy (1961) and Slatt (1970) have found appreciable quantities of dissolved ions in glacial streams. In 1928, V. M. Goldschmidt published a note in which he described materials of laterite composition formed from anorthosites in the alpine zone of Norway. Except for this single observation, the occurrence of bauxite material on bare, alpine slopes is apparently at variance with conventionally accepted concepts that limit such silica-deficient materials to the environment of a tropical savanna. A closer examination of the local chemical environment in the high peak regions provides a basis for resolving this apparent anomaly. Like the tropical savanna, the alpine region is subject to seasonal drought. Large amounts of water (~ 400 cm/yr) pour over these slopes during spring and summer during the period of snowpack melt. By August, the slopes are dry due to solar insolation. The region is subject to intense leaching and high local temperatures for some months each year. Berner (1971), basing his arguments on experimental measurements of feldspar dissolution rates (Wollast, 1967), concludes that the rate of leaching exerts important controls on the formation of kaolinite and gibbsite. High leaching rates favor gibbsite, whereas lower rates favor the formation of kaolinite. The pH of associated waters is another important consideration. According to Curtis (1970), pH values between 6 and 7 are optimum for bauxite formation because at these hydrogen-ion concentrations, the solubility ration of $Al(OH)_3/SiO_2$ is at a minimum. Waters seeping through the thin and discontinuous alpine bauxite lithosols have been studied, and they have pH values between 6·5 and 7·2. The pH values are apparently the result of hydrolysis reactions with parent bedrock, the presence of atmospheric CO_2 (carbonation), and the virtual absence of organic acids. Thus, it seems that the requisite conditions are present in this particular alpine region for bauxite formation.

Alpine terrain is generally devoid of vegetation and soil. Air temperatures are low and, for many months of the year, rock surfaces may be dry because local water is locked up as snow and ice. Evidence of vigorous mechanical weathering is widespread. These conditions taken by themselves may lead to the conclusion that chemical weathering activity is nil.

An accurate evaluation of chemical weathering must take into account other factors. Soil accumulation is a function of both formation and erosion rates. Erosion rates are high in alpine mountains and appreciable soil formation can occur and leave little or no record. The absence of soils is, therefore, not a valid criterion for discounting the operation of pedogneic processes.

Prevailing low temperatures may be cited as conducive to low chemical reaction rates. If rock surfaces are below the freezing point, this argument has some validity. But cold waters can be chemically reactive. The work of Tamm (1924) showed that dissolution rates of common rock-forming silicate minerals in water were relatively constant over the range of 2–15°C, so low water temperatures are probably not an inhibiting factor for clay-forming processes in an alpine environment.

The local low air temperatures should not necessarily be equated with low rock surface temperatures. In this connection, a colleague, W. Campbell, has measured rock surface temperatures by i.r. radiometry on the cliffs surrounding South Cascade Glacier. He reports values as high as 40°C on favorably situated mountain faces, and has formed the opinion that much of the rock exposed to the sun above snow line is above the freezing point during the winter days. Thus it seems that low mean annual air temperatures in alpine terrain need not necessarily limit chemical weathering processes.

The presence of alpine glaciers in North America generally attests to high local precipitation intensities. If the glacial budget is balanced, then proportional amounts of runoff must occur. This involves great hydrologic activity with attendent chemical leaching. The water is chemically corrosive because it is continuously recharged with CO_2 (Johnson, Reynolds and Campbell, 1970). The runoff encounters high unit surface area rock material such as glacial rock flour, scree, and shattered cliff faces. In addition, fresh rock surface area is continuously maintained by high erosion rates. These conditions provide an optimum environment for chemical attack and clay mineral formation.

The evidences presented by this paper, and an examination of the local prevailing environmental conditions, lead to the conclusion that the maritime glacial environment of the high Cascades is a dynamic chemical system in which chemical weathering and clay mineral formation are vitally involved. To the extent that these conclusions are applicable to other alpine and/or arctic environments, some reconsideration may be in order for contemporary concepts regarding, (1) climatic interpretations based on paleosols, (2) the effects of Pleistocene glaciation on the chemistry of peripheral terrigenous and marine systems, and (3) the control exerted by climate on the geochemical cycle.

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Résumé — De la vermiculite, un interstratifié vermiculite-phlogopite, et une smectite, se forment actuellement à partir de roches mère ignées et métamorphiques, dans la zone alpine des Northern Cascades, Washington. En plus, des quartz-diorites et des métadiorites situées au-dessus de la limite des neiges sur les versants face au Sud s'altèrent en bauxites ferrugineuses. Les calculs indiquent que la vermiculite est actuellement en formation à partir des schistes phlogopitiques de ce milieu, à une vitesse, par unité de surface, qui est approximativement six fois la vitesse moyenne estimée pour l'érosion de l'argile dans l'Amérique du Nord. Les données minéralogiques indiquent que l'altération chimique est, dans cette région, un processus quantitativement significatif, et suggèrent que dans le développement des concepts géomorphologiques courants, les chercheurs peuvent avoir généralement sous-estimé l'importance de l'altération chimique dans les milieux alpins.

Kurzreferat — Vermiculit, gemischt schichtiger Vermiculit-Phlogopit und Smectit werden gegenwärtig aus eruptivem und metamorphem Grundgestein in der alpinen Zone der nördlichen Cascades, Washington, gebildet. Darüber hinaus verwittern gegen den Süden weisende Quarz-Dioriten und Metadioriten oberhalb der Schneegrenze zu eisenschüssigem Bauxit. Berechnungen ergeben, dass sich Vermiculit gegenwärtig aus Phlogopitschiefern in diesem Milieur mit Einheitsflächengeschwindigkeit bildet, das ist etwa sechsmal der durchschnittlichen Schätzgeschwindigkeit der Tonerosion in

Nordamerika. Die mineralogischen Messwerte deuten darauf hin, dass chemische Verwitterung in dieser Gegend ein quantitativ bedeutsamer Vorgang ist, und geben zu der Vermutung Anlass, dass bei der Entwicklung laufender geomorphischer Begriffe die Forschung möglicherweise die Bedeutung der chemischen Verwitterung in der alpinen Umgebung unterschätzt hat.

Резюме — В альпийской зоне северной части Каскадов (шт. Вашингтон) происходит современное образование вермикулита, смешаннослойного вермикулит-флогопита и смектита по изверженным и метаморфическим породам. Кроме того обращенные к югу обнажения кварцевых диоритов и метадиоритов выше снеговой линии выветриваются с образованием железистого боксита. Проведенные вычисления показывают, что вермикулит в настоящее время образуется из флогопитовых сланцев со скоростью на единицу поверхности, которая примерно в 6 раз превышает среднюю скорость эрозии Северной Америки. Мниералогические данные указывают, что химическое выветривание в этом регионе вызывает преобразование значительного количества материала и дает возможность предположить, что при развитии современных геоморфологических концепций исследователи, возможно, обычно недооценивают роль химического выветривания в условиях альпийского рельефа.