(2) those formed during previous stabilizations of the main river at grades higher than the present. Terraces of the first type have no chronologic significance. Of the latter type, terraces from 10 to 100 feet above the present river grade are known and doubtless represent the events of late Pleistocene time.

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(22)

A STUDY IN ROCK-WEATHERING

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ABSTRACT

Four districts furnished samples for a study in rock-weathering. Mineralogical data and fourteen new chemical analyses are presented in tables and diagrams. The granite gneiss of Morton, Minnesota, shows a marked loss of soda and lime in early stages of weathering but a more gradual loss of potash and baria. The progress of the decomposition is interpreted from a series of six samples of residual clay. Kaolinite is an end product.

New chemical analyses of material from the Medford, Massachusetts, diabase are presented as a check on the older data. Ferrous and ferric iron determinations on samples of diabase and of glacial till suggest that the till is less oxidized than the underlying diabase, indicating preglacial weathering of the diabase.

A diabase on the north shore of Lake Superior, Minnesota, is weathered locally to a depth of 40 feet but shows little chemical change except oxidation.

An amphibolite from the Black Hills, South Dakota, yielded beidellite or related clay minerals by decomposition of its hornblende. Calcite has been leached, and other minerals attacked.

On the basis of the present and earlier studies, a *mineral-stability series in weathering* is proposed. The arrangement of the common rock-forming minerals in this series is found to coincide with the reaction series. Experimental work on the attack of silicate minerals by water is in accord with the suggested mineral-stability series.

INTRODUCTION

The effects of rock-weathering have long been observed and studied, and the interest in this field of geological investigation is indicated by a voluminous literature. With the increasing emphasis on sedimentation and on the origin and development of soils, the basic contributions of studies in weathering assume even greater significance.

The present study is an attempt to analyze the chemical and mineralogical changes produced in the weathering of certain rocks from a few localities selected chiefly because of their accessibility to the writer or because suitable samples were available. The rocks and their weathering products studied are the following: (1) granite gneiss from the vicinity of Morton, Minnesota; (2) diabase from Medford, Massachusetts; (3) diabase from the north shore of Lake Superior, Minnesota; (4) amphibolite from the Black Hills, South Dakota.

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F. F. Grout and G. A. Thiel, of the University of Minnesota, and to Dr. R. B. Ellestad, of the Rock Analysis Laboratory of that institution for many suggestions and criticisms which aided in the development of the problem. Mr. Robert Grogan assisted in the field work. Thanks are due to Professor C. L. Baker and Dr. F. E. Turner, of the Agricultural and Mechanical College of Texas, for their critical reading of the manuscript.

METHODS OF STUDY

CHEMICAL ANALYSIS

The new chemical analyses presented in this paper were made in the Rock Analysis Laboratory in the Department of Geology of the University of Minnesota. The methods routinely employed in that laboratory are essentially those described by Hillebrand and Lundell.[1]

SPECIFIC GRAVITY

Determinations of specific gravity were made with the fused silica pycnometer designed and described by Ellsworth.[2] Tables and charts prepared by Dr. R. B. Ellestad facilitated the calculations and the application of buoyancy corrections.

MINERALOGICAL STUDY

Most students of weathering have relied on chemical data and on calculations based on these data for a quantitative measure of rock decomposition. Inferences can be made from chemical analyses as to the mineralogical changes which have taken place. Nevertheless, it seems desirable to attempt some correlation between the changes indicated by the analytical results and the actual mineral changes. In the mineralogical study a combination of methods was used. A technique involving the use of a heavy liquid and a multiple-type of electromagnetic separator may warrant brief description. The general procedure is used extensively in sedimentation and in accessory mineral studies.

Samples of both fresh and weathered material were crushed to

[1] W. F. Hillebrand and G. E. F. Lundell, *Applied Inorganic Analysis* (New York: John Wiley & Sons, 1929).

[2] H. V. Ellsworth, "A Simple and Accurate Constant-Volume Pyknometer for Specific Gravity Determinations," *Min. Mag.*, Vol. XXI (1928), pp. 431–36.

reduce the rock aggregate as much as possible to monomineralic particles. The pulverized samples were washed with water, and the fraction remaining in suspension after a settling period of three minutes in a 5-inch column of water was removed by siphoning.

The washed samples after being dried were separated by means of bromoform (sp. gr. = 2.88) into a light and heavy fraction. The light fractions were bottled and reserved for study. The heavy-mineral fractions were further split by electromagnets into four separates of different magnetic susceptibility. These separates were weighed, and a portion of each, obtained with a micro-splitter, was mounted in Canada balsam. The relative proportions of the minerals in each separate were determined by counting. From the frequency percentages, the approximate weight of each mineral in all four separates was obtained and converted into the final percentage representing the approximate percentage by weight of the mineral in the heavy-mineral fraction.

The heavy-mineral technique was introduced as an experiment. It affords the advantage of permitting both fresh and weathered material to be treated by a single procedure.

CALCULATIONS AND DIAGRAMS

A variety of diagrams have been used by geologists to show the effects of weathering. The "straight-line" diagram[3] is used to show the relative gains and losses during rock alteration when no single constituent is assumed to have remained constant. The *Al-C-Alk* relationship proposed by Osann[4] is based on the proportions of alumina, lime, and alkalies. The molecular percentages of Al_2O_3, (Ca,Ba)O, and $(Na,K)_2O$ are recalculated to 30 and are plotted on a triangular diagram. According to Osann, all igneous rocks should fall to the right of the line which divides the triangle (Fig. 8) into two fields. Sedimentary and parametamorphic rocks fall in the field to the left of the line. Other calculations and diagrams used for single groups of analyses are discussed in appropriate places.

[3] C. K. Leith and W. J. Mead, *Metamorphic Geology* (New York: Henry Holt & Co., 1915), p. 288.

[4] Rosenbusch-Osann, *Elemente der Gesteinslehre* (4th ed.; Stuttgart, 1923), pp 96–104, Pl. III.

MORTON GNEISS

GENERAL STATEMENT

Residual clays in the vicinities of Morton and Redwood Falls, Minnesota, were formed by pre-Cretaceous weathering of a granite gneiss. The fresh gneiss is well exposed in a number of quarries which have been described recently by Thiel and Dutton.[5] The residual clays are overlain by Cretaceous sediments or by glacial drift in places where the Cretaceous has been eroded. The clays of this region have been studied by Winchell,[6] by Upham,[7] by Hall,[8] by Meinzer,[9] and more recently by Grout.[10] Six samples of residual clay were studied for comparison with the fresh Morton gneiss. The locations of the samples are shown in Figure 1, and chemical analyses are given in Table 1. For comparison, analyses of fresh and decomposed gneiss previously published are included in the table.

FRESH MORTON GNEISS

Location and description of sample.—The Morton quarry of the Cold Spring Granite Company (Sec. 31, T. 113 N., R. 34 W.) is the largest in the district and affords the best possibilities for sampling. The gneiss is pink to dark gray. Quartz, pink to red potash feldspar, light-colored plagioclase, biotite, and magnetite are easily recognizable. The dark- and light-colored minerals are more or less segregated into bands. The texture is porphyritic and in some places pegmatitic. Pegmatites, quartz veins, and fine-grained granitic dikes of reddish color cut the gneiss.

Fourteen pounds of chips were taken from blocks and from quarry ledges and walls. The final sample (No. 1) was a composite of mate-

[5] G. A. Thiel and C. E. Dutton, "The Architectural, Structural and Monumental Stones of Minnesota," *Minn. Geol. Surv. Bull. 25* (1935), pp. 88–95.

[6] N. H. Winchell, *Geol. and Nat. Hist. Surv. Minn., 2d Ann. Rept.* (1874), p. 163; and *Geol. Minn.*, Vol. I (1882), p. 571.

[7] Warren Upham, "The Geology of Renville County," *Geol. and Nat. Hist. Surv. Minn.*, Vol. II (1888), pp. 190–204.

[8] C. W. Hall, "The Gneisses, Gabbro-Schists, and Associated Rocks of Southwestern Minnesota," *U.S. Geol. Surv. Bull. 157* (1899).

[9] C. W. Hall, O. E. Meinzer, and M. L. Fuller, "Geology and Underground Waters of Southern Minnesota," *U.S. Geol. Surv. Water-Supply Paper 256* (1911), pp. 304–24.

[10] F. F. Grout, "Clay and Shales of Minnesota," *U.S. Geol. Surv. Bull. 678* (1919), pp. 78–80, 216–22.

rial collected on different days by three men and is considered to be fairly representative of the gneiss in the quarry. Whether or not the sample is representative of all the bedrock in this portion of the

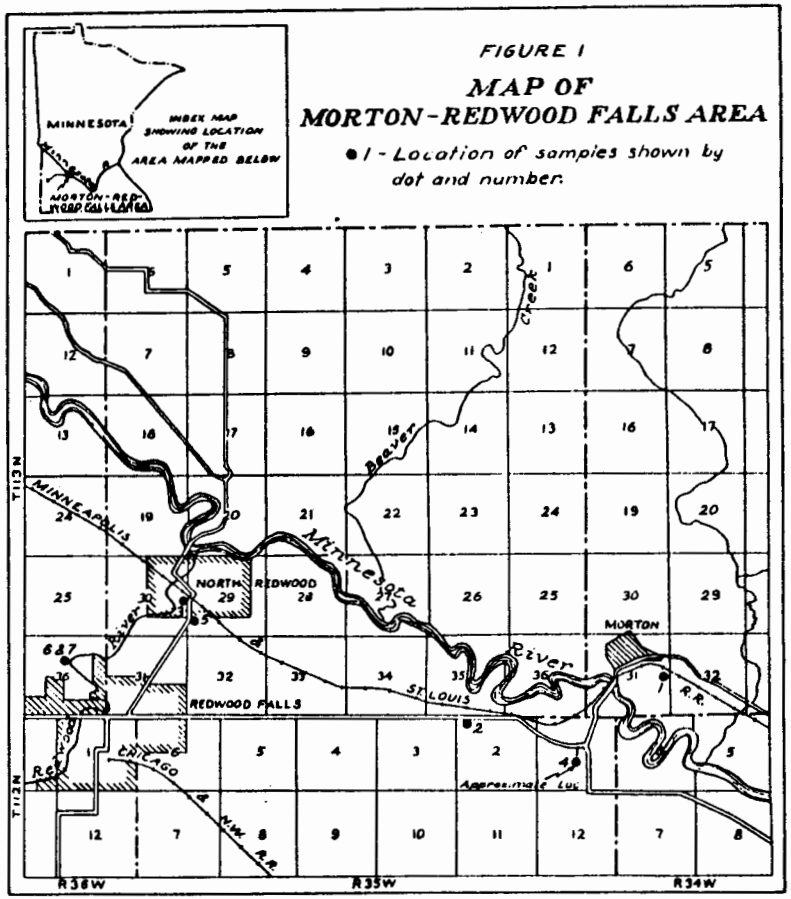

FIG. 1.—Map of Morton–Redwood Falls area

valley is open to some doubt. The selection of material would influence the results. However, the origin of the gneiss and the field relationships suggest that some differences may be expected in the parent-rock from which the residual clays in the Morton–Redwood Falls area have been derived.

The Morton gneiss is an injection gneiss—a hybrid formed by the invasion of schists (?) by a granitic magma. In smaller quarries about 1½ miles north of North Redwood (NW. ¼ Sec. 29, T. 113 N., R. 35 W.) banded gneiss similar in appearance to the rock in the Morton quarries grades into medium-grained granite.

TABLE 1

CHEMICAL ANALYSES OF FRESH AND WEATHERED GNEISS FROM MORTON–REDWOOD FALLS AREA

	1	2	3	4	5	6	7	8	9
SiO_2	71.54	69.89	68.09	61.75	70.30	57.53	55.07	63.61	60.61
Al_2O_3	14.62	16.54	17.31	18.58	18.34	23.57	26.14	16.71	18.12
Fe_2O_3	0.69	2.33	3.86	1.69	1.55	3.05	3.72	5.69	7.51
FeO	1.64	0.34	0.36	4.11	0.22	3.59	2.53	2.78	
MgO	0.77	0.30	0.46	0.76	0.21	0.41	0.33	1.63	1.14
CaO	2.08	0.06	0.06	0.16	0.10	0.05	0.16	4.03	0.03
Na_2O	3.84	0.43	0.12	0.10	0.09	0.06	0.05	1.68	0.54
K_2O	3.92	5.34	3.48	3.54	2.47	0.35	0.14	2.49	3.56
H_2O+	0.30	4.00	5.14	5.56	5.58	8.82	9.75	0.61	7.20*
H_2O-	0.02	0.35	0.47	0.35	0.30	0.70	0.64	.....	0.28
CO_2	0.14	0.21	0.05	1.84	0.20	0.77	0.36	.....	.....
TiO_2	0.26	0.14	0.34	0.92	0.21	0.87	1.03	.....	1.30
P_2O_5	0.10	0.04	0.03	0.09	0.04	0.08	0.11	0.25	.....
MnO	0.04	0.04	0.06	0.21	0.03	0.07	0.03	.....	.....
BaO	0.09	0.13	0.07	0.09	0.05	Tr.	0.01	.....	.....
SO_3	n.d.	Tr.	0.00	0.03	0.00	Tr.	Tr.	.....	.....
S	0.02	0.01	0.01	0.05	0.01	0.01	0.04	.....	.....
Total	100.07	100.15	99.91	99.83	99.70	99.93	100.11	99.48	100.29
Sp. gr. $t°/4°$	2.670	2.616	2.642	2.682	2.632	2.671	2.658	.....	.....

* Loss on ignition.

1. Granite gneiss, Cold Spring Granite Company quarry, Morton, Minnesota. S. S. Goldich, analyst.
2–7. Residual clays from Morton–Redwood Falls area; locations given in Fig. 1. See also the text. S. S. Goldich, analyst.
8. Hornblende-biotite-gneiss of Morton. *U.S. Geol. Surv. Bull. 157* (1899), p. 75. A. D. Meeds, analyst.
9. Decomposed gneiss from locality south of Morton. *U.S. Geol. Surv. Bull. 678* (1919), p. 217. F. F. Grout, analyst.

Petrography.—The essential minerals of the gneiss are oligoclase, orthoclase, microcline, quartz, biotite, and hornblende. Accessory minerals are magnetite, apatite, titanite, allanite, and zircon. Secondary products—sericite, chlorite, epidote, calcite, leucoxene, and

pyrite—are not abundant. The plagioclase is zoned irregular and the more calcic portions are sericitized. Irregularities in extinction suggest a lack of homogeneity which may have resulted from magmatic evolution and probably also from contamination.

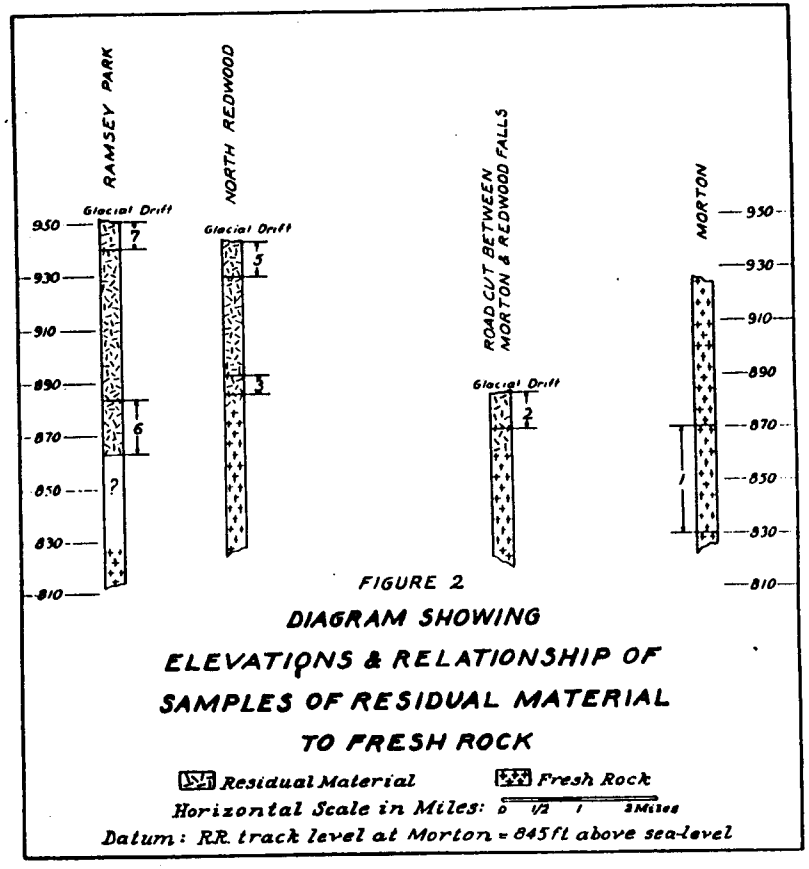

FIG. 2.—Diagram showing elevations and relationship of samples of residual material to fresh rock.

Thiel and Dutton[11] have classed the Morton rock as granite gneiss, but the calcic character of the gneiss should be noted. This is a result of reaction between the granitic magma and the minerals of the schist. The conversion of hornblende to biotite with the con-

[11] *Op. cit.*, p. 88.

sequent freeing of lime no doubt made the feldspar more calcic. The estimated mineralogical composition (Table 6) suggests a quartz monzonite. In Johannsen's classification, *adamellite* would be appropriate. In the C.I.P.W. system, the rock is *toscanose*.

RESIDUAL CLAYS

Field relationships.—Weathering in the Morton–Redwood Falls area has not proceeded uniformly. In the uppermost part of the

FIG. 3.—Residual clay along the highway between Redwood Falls and North Redwood.

quarry at Morton, weathering has a definite relationship to the jointing. Spheroidal weathering was probably initiated at considerable depth below the surface. In the exposures of residual clay less altered portions, frequently pegmatitic zones, protrude as ridges (Figs. 3 and 4).

In all the outcrops sampled some evidence of the nature of the original rock can be found in texture and in structures which have been retained. The less altered portions were of aid in determining the parent-gneiss. The abundance of quartz grains in the residual clay indicates a granite gneiss not very different from that exposed at Morton. Quartz veins, though somewhat shattered and broken,

can be traced vertically from the base to the top of certain outcrops, and these together with color banding inherited from the gneiss show the residual character of the clay.

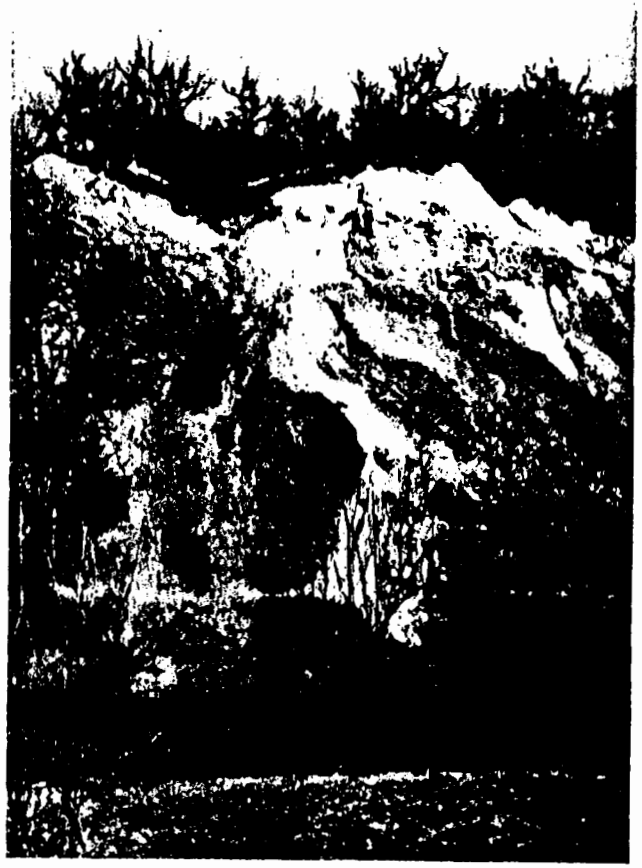

FIG. 4.—Bluff of irregularly weathered gneiss in Ramsey State Park, Redwood Falls.

Location and description of samples.—The residual clays were sampled by channeling the exposures. The elevations given for the samples were taken with a Paulin surveying aneroid. The relationships are shown in Figure 2.

Sample No. 2: Elevation of base, 871 feet. Tan-colored residual clay in a road-cut on the south side of U.S. Highway No. 71 between

rton and Redwood Falls was sampled in a 12-foot vertical section. Quartz grains and partially kaolinized feldspar are visible. The presence of knobs of fresh gneiss near by at an elevation of 850 feet and the lateral gradation of the residual clay in the road-cut into comparatively fresh gneiss suggest that the material represented in the sample is not far removed from bedrock.

Sample No. 3: Elevation of base, 885 feet. The sample was taken from an exposure along the highway between Redwood Falls and North Redwood about $\frac{1}{10}$ mile south of the intersection of the highway and the railroad tracks in North Redwood. The dry material is brown. Quartz and altered feldspar are conspicuous.

Sample No. 4: Dark-gray clay collected and described by Grout: "Between Redwood Falls and Morton, on the south bank of Minnesota River, a test pit has been dug by the Morton Brick and Tile Co. into a bank of residual decomposed gneiss, which has retained its granitoid texture."[12]

Sample No. 5: Elevation of base, 929 feet. The sample represents the upper 13 feet of about 25 feet of clay on the east side of the highway from Redwood Falls to North Redwood uphill from sample No. 3. The dry color is light gray. The base of the sample is about 38 feet above the top of sample No. 3.

Sample No. 6: Elevation of base, 863 feet. Light-green to gray clays extend to a depth exceeding 90 feet. The sample is from a 20-foot vertical channel, the base being a few feet above river level.

Sample No. 7: Elevation of base, 940 feet. Sample of 10 feet of yellow-brown clay from the top of bluff above sample No. 6. No definite structure is visible, and the clay appears uniform and compact.

Mineralogy of the residual clays.—The residual clays are composed chiefly of kaolinite and quartz, the latter derived from the original mineral of the gneiss. Other original minerals are not common. Besides the kaolinite and other clay minerals not positively identified, iron oxides, siderite, leucoxene, and a chlorite-like mineral are weathering products.

Quartz: The analyses in Table 1 are arranged in order of increasing water content, which might be taken as an indication of the ex-

[12] *Op. cit.*, p. 217.

tent of decomposition. It will be noted that an increase in water over that contained in the fresh gneiss is accompanied by an increase in alumina and, in general, by a decrease in silica. The series for silica, however, is not a regular one, and in order to determine to what extent the silica content is influenced by the amount of quartz present, quantitative study of the quartz was attempted by the method suggested by Knopf.[13] This method is based on the solubility of silicate minerals in hydrofluosilicic acid, which does not attack quartz appreciably. A definite correlation is found between the quartz and the silica contents of the samples; high silica in a clay sample reflects a high quartz content.

TABLE 2

QUARTZ CONTENT OF RESIDUAL CLAY SAMPLES*

	1	2	3	4	5	6	7
SiO_2	71.54	69.89	68.09	61.75	70.30	57.53	55.07
Quartz	28.4	35.0	38.7	31.7	41.9	26.3	24.9

* Estimated by the hydrofluosilicic acid method. The quartz of sample No. 1 is normative quartz. The silica percentages are from Table 1.

Clay mineral: The chief clay mineral formed by the decomposition of the silicates of the gneiss is kaolinite ($H_4Al_2Si_2O_9$). The composition of the clay mineral was first demonstrated by partial chemical analyses quoted in Table 3. More recent analyses of the clays in the lower part of the Cretaceous formation are included in the table. These clays were derived by the re-working of the weathering products of the gneiss in this region. A sample of the white clay from the Cretaceous collected by Gilman Berg was x-rayed by Professor J. W. Gruner, of the University of Minnesota, who reported the pattern as that of kaolinite.[14]

In the residual clays some nontronite, or iron-bearing clay mineral, may be present. A green micaceous mineral apparently derived from the biotite of the gneiss approaches kaolinite in composition.

Heavy minerals: Bromoform separations were made on the

[13] Adolph Knopf, "The Quantitative Determination of Quartz in Dusts," *U.S. Public Health Service Reports*, Vol. XLVIII, No. 8 (1933), pp. 183–90.

[14] Verbal communication from Mr. Berg, 1935.

washed samples of the fresh gneiss and the residual clays according to the procedure described. The heavy mineral analyses are given in Table 4. Much of the ilmenite in the clay samples is fresh, but grains in various stages of alteration are most abundant. Limonite,

TABLE 3

ANALYSES OF CRETACEOUS CLAYS AND CLAY WASHED FROM WEATHERED GNEISS

	1	2	3	4
SiO_2	43.86	45.92	45.14	44.12
Al_2O_3	41.82†	39.84†	37.94	38.39
Fe_2O_3	41.82†	39.84†	1.01	1.06
FeO	41.82†	39.84†	1.01	1.06
MgO, CaO	Very small	Very small	0.08, 0.46	0.11, 0.28
Na_2O	n.d.	n.d.	0.36	0.30
K_2O	n.d.	n.d.	0.09	0.17
H_2O*	14.65	14.12	14.10	14.70
TiO_2	.....	.....	1.09	1.17
Total	100.33	99.88	100.27	100.30

* H_2O by ignition.

† With the alumina of No. 1 is associated a trace of iron and with that of No. 2 a little iron and about 0.3 per cent of TiO_2.

1. Clay from Morton. *U.S. Geol. Surv. Water-Supply Paper 256* (1911), p. 310. F. F. Grout, analyst.
2. Clay washed from a decomposed granite, Redwood Falls. *Ibid.* F. F. Grout, analyst.
3. Smooth white clay from Cretaceous deposits near Morton. *U.S. Geol. Surv. Bull. 678* (1919), p. 219. Analysis by Bureau of Standards.
4. Concretionary clay from Cretaceous deposits near Morton. *Ibid.* Analysis by Bureau of Standards.

hematite, and leucoxene stained by secondary iron oxides could not be differentiated readily and were counted together. Similarly, biotite grades into a green mineral counted as chlorite.

Biotite in the gneiss as well as some of the unaltered mineral in certain clay samples gave beta = 1.640. The green micaceous mineral in the heavy mineral fractions has a lower refractive index. Further weathering of this mineral seems to leach it to such an extent that it floats on bromoform. Flakes of a faint greenish color in the light mineral fractions gave beta = 1.570, and flakes of essentially

TABLE 4

HEAVY-MINERAL ANALYSES OF FRESH GNEISS AND RESIDUAL CLAYS IN THE MORTON–REDWOOD FALLS AREA

	1	2	3	4	5	6	7
Washed sample (percentage weight of original)	91.0	63.4	60.8	60.0	58.0	62.8	56.0
Heavy fraction (percentage weight of washed sample)	7.36	2.62	4.05	9.54	1.37	3.45	3.10
	Percentage approximate weight of total heavy minerals						
Minerals:							
Allanite	0.06	*	*	*	*	*	*
Apatite	1.91	.04	Tr.	0.01	Tr.	0.03	0.03
Biotite	76.89	18.55	0.70	29.20	0.68	Tr.	0.00
Chlorite	Present	Present	.....	Present	.....	11.10	4.89
Collophane(?)	None	0.33	0.00	0.01	0.01	?	?
Epidote	2.24	0.09	0.14	1.78	0.36	0.19	0.24
Hornblende	9.84	0.13	0.00	0.03	0.00	2.50	0.33
Ilmenite, Leucoxene, Limonite and hematite, Magnetite	2.27, 0.11, 0.01, 5.65	79.73	98.34	19.55	97.05	70.14	86.00
Pyrite	0.05	0.07	Tr.	0.02	0.01	0.03	0.29
Siderite	None	0.28	0.05	48.53	0.18	11.62	5.13
Titanite	0.49	0.00	0.00	0.01	0.01	0.00	0.00
Zircon	0.43	0.74	0.76	0.81	1.68	4.36	3.09
Unknown	0.05	0.04	0.01	0.05	0.02	0.03	0.00
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* Included with epidote.

the same appearance but colorless have an index of refraction of about 1.565 in basal section. This mineral is probably kaolinite. A

lar alteration of biotite to kaolinite has been described by Tulli and Laney,[15] who found that a green micaceous mineral represents an intermediate stage in the alteration. These men question the identity of this product with chlorite.

Light Minerals: Of particular interest is the feldspar content of the light fractions obtained from bromoform separations. Frequency percentages of the quartz and feldspar in these fractions are given in Table 5. Besides the quartz and feldspar of sample No. 1, a small amount of biotite and chlorite is listed as "other minerals." The feldspar of the residual clay samples is almost wholly composed of the potash feldspars, orthoclase and microcline. Kaolinite and the greenish, chlorite-like mineral constitute the remaining minerals.

TABLE 5

MINERALOGICAL ANALYSES OF LIGHT FRACTIONS OF WASHED SAMPLES

	1	2	3	4	5	6	7
Quartz	48	41	54	41	60	n.d.	n.d.
Feldspar	48	38	23	21	21	None	None
Others	4	21	23	38	19	n.d.	n.d.

ESTIMATED MINERALOGICAL COMPOSITION OF FRESH AND WEATHERED SAMPLES

The mineralogical compositions of the clay samples and of the fresh Morton gneiss were estimated from the results of the mineralogical study in conjunction with the chemical data. It is difficult to state the accuracy of the estimates in Table 6, but the different sources of information used in the compilation afforded some check on the reasonableness of the results. Thus a rough estimate of the potash feldspar can be made from the light-mineral analyses and can be checked by the potash available in the chemical analyses.

After allotting various oxides to the minerals known to be present in accordance with calculations similar to those employed in the C.I.P.W. system, the residual silica was allotted to quartz. In every case, the calculated quartz approached within 10 per cent of the values obtained in the quartz determinations listed in Table 2.

[15] E. L. Tullis and F. B. Laney, "The Composition and Origin of Certain Commercial Clays of Northern Idaho," *Econ. Geol.*, Vol. XXVIII (1933), p. 487.

CHEMICAL AND MINERALOGICAL CHANGES

The chemical and mineralogical changes resulting from the weathering of the gneiss in the Morton-Redwood Falls area are shown in a series of diagrams (Figs. 5, 6, 7, and 8). These will be considered at this time.

TABLE 6

MINERALOGICAL COMPOSITION OF THE MORTON GNEISS AND RESIDUAL CLAYS ESTIMATED FROM MINERAL AND CHEMICAL ANALYSES

	1	2	3	4	5	6	7
Quartz	30.0	35.0	40.0	31.0	43.0	28.0	25.0
Potash feldspar	19.0	31.0	18.0	19.0	13.0	2.0 (?)	1.0 (?)
Plagioclase	40.0	4.0	1.0	1.0	1.0	?	?
Biotite (Chlorite)	7.0	0.8	Tr.	4.0	Tr.	0.5	0.2
Hornblende	1.0	Tr.	None	Tr.	None	0.1	Tr.
Magnetite	1.0	3.0	5.0	4.0	2.0	6.0	6.0
Ilmenite	0.5						
Leucoxene and secondary iron oxides	Tr.						
Calcite	0.3	.....	.....	.....	.....	.....	.....
Siderite	.....	0.6	0.1	5.0	0.5	2.0	0.9
Titanite	0.04	None	None	Tr.	Tr.	None	None
Epidote	0.2	Tr.	Tr.	0.2	Tr.	Tr.	Tr.
Apatite	0.2	Tr.	Tr.	Tr.	Tr.	Tr.	Tr.
Zircon	0.02	0.02	0.03	0.08	0.02	0.15	0.10
Allanite	Tr.	.....	.....	.....	.....	.....	.....
Kaolin	.....	26.0	36.0	35.0	40.0	59.0	66.0

"Straight-line" diagram.—Figure 5 is a "straight-line" diagram in which the residual clay samples have been compared with the fresh gneiss in the Morton quarry. If alumina is considered to have remained constant during the weathering process, the constituents of any one sample, which fall to the right of the point indicating alumina for that sample, have been lost; those to the left, gained. The pattern developed in the diagram indicates some degree of uniformity in the behavior of most of the constituents.

The progressive alterations shown by K_2O and BaO in Figure 5 and their close relationship are noteworthy as is the more erratic behavior of FeO and CO_2. Residual clays containing appreciable amounts of ferrous iron also have considerable carbon dioxide, and in these samples siderite is found. Siderite composes about 5 per

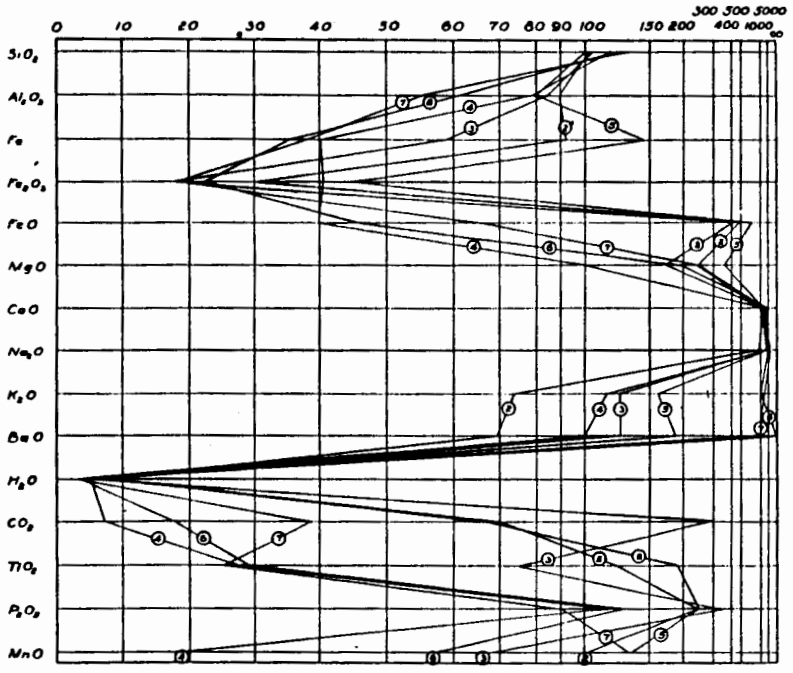

FIG. 5.—Representing the losses and gains of constituents by weathering of gneiss in the Morton-Redwood Falls area.

cent of sample No. 4. Under the usual conditions of weathering prevailing at the surface, ferrous iron is oxidized. The more or less hydrated ferric oxides are relatively stable, but, in the presence of reducing agents, iron may be taken into solution. Solution and transportation of iron as the bicarbonate apparently did take place in this region. Downward migration with subsequent precipitation as the carbonate may be in part the cause for the differences in iron content of the samples. There may have been differences in the original material also, and the behavior of TiO_2 and MnO is suggestive of such differences.

Variation diagrams.—Variation diagrams are useful in showing relationships in a rock series. In Figure 6 the variation curve for lime and soda each follows that of plagioclase. The oligoclase of the

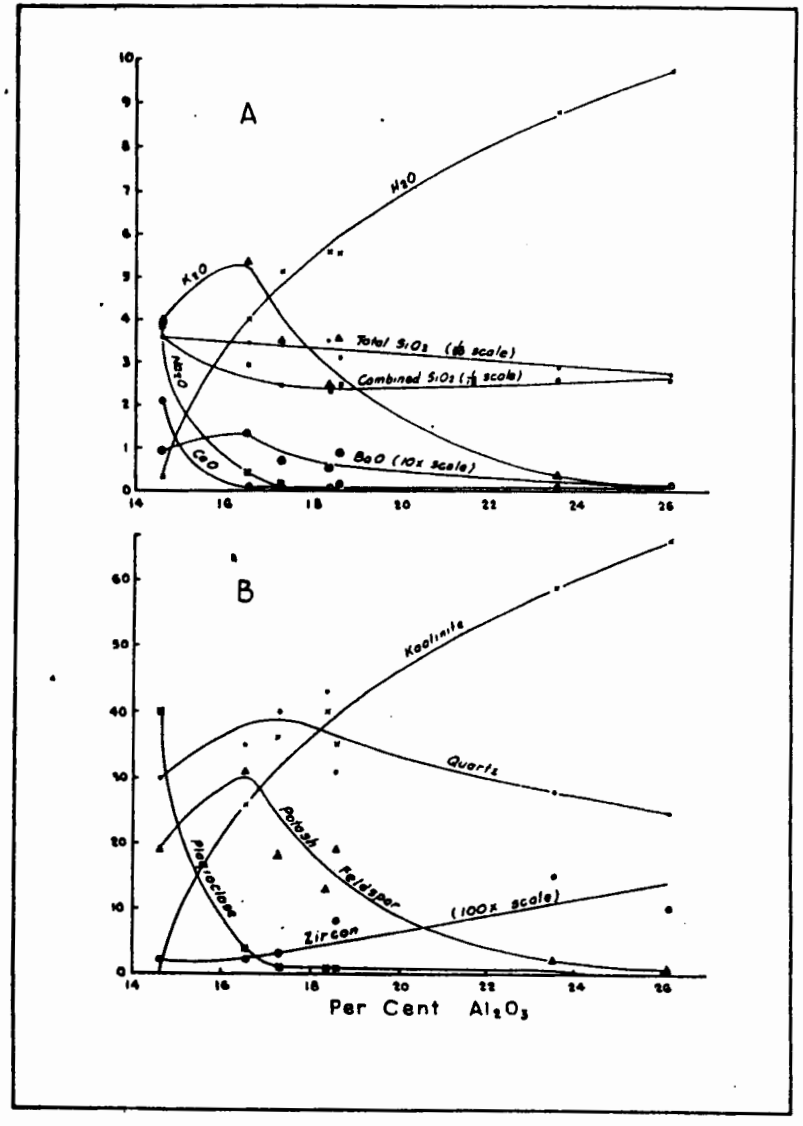

FIG. 6.—Variation diagrams of the series of fresh and decomposed granite gneiss samples from the Morton-Redwood Falls area.

gneiss is readily attacked, and the lime, soda, and some of the silica are removed. In contrast with these curves, potash and potash feldspar curves show an upward trend in the early stages of weathering. The feldspar of the light-mineral fractions is largely potash feldspar, and it is believed that the early destruction of the plagioclase results in a mechanical concentration of the orthoclase and microcline. Thus in sample No. 2, potash feldspar is estimated to compose about 35 per cent of the clay.

The behavior of baria is of interest in connection with the alteration of the feldspar. Baria is usually considered to be closely related to lime, and rules for calculations involving chemical analyses commonly call for the addition of baria to the lime. Inspection of the chemical analyses, however, reveals no correlation between the amounts of lime and baria, but rather one between potash and baria. This is clearly shown in Figure 5. The presence of baria in some potash feldspars is well known. The barium molecule, $BaAl_2Si_2O_8$, celsian, enters into solid solution with the orthoclase molecule, $KAlSi_3O_8$. In the series of samples from the Morton–Redwood Falls area some of the potash must be assigned to biotite. Biotite, however, is not abundant, and in the residual clays the potash and baria can be correlated with the potash feldspar content of the clays. Only when the orthoclase and microcline have been thoroughly decomposed are the potash and baria largely removed. Such a condition of profound leaching has been attained in samples No. 6 and No. 7, and the chemical analyses of these samples reveal only small amounts of potash and traces of baria.

It has been suggested that the decomposition of the plagioclase in the early stages of weathering results in a mechanical concentration of the more resistant orthoclase and microcline. Similarly, the decomposition of the feldspar causes an apparent increase in the quartz content of the clay samples, but the high point in the quartz curve beyond which it declines comes at a later stage in the weathering process. The total silica curve shows a decline along an essentially straight line. Actually, this curve is a composite of the "combined" silica curve (Fig. 6*A*) and of a quartz curve such as the one shown in Figure 6*B*. The decomposition of the feldspar with the loss of silica is reflected in the downward slope of the combined silica

curve, but at the same time the quartz curve is ascending, compensating for the loss of silica from the destruction of silicates. Finally, after more or less complete alteration of the original aluminum silicates to the stable product, kaolinite, quartz is slowly dissolved, and both the curve for quartz and that for total silica have a downward slope.

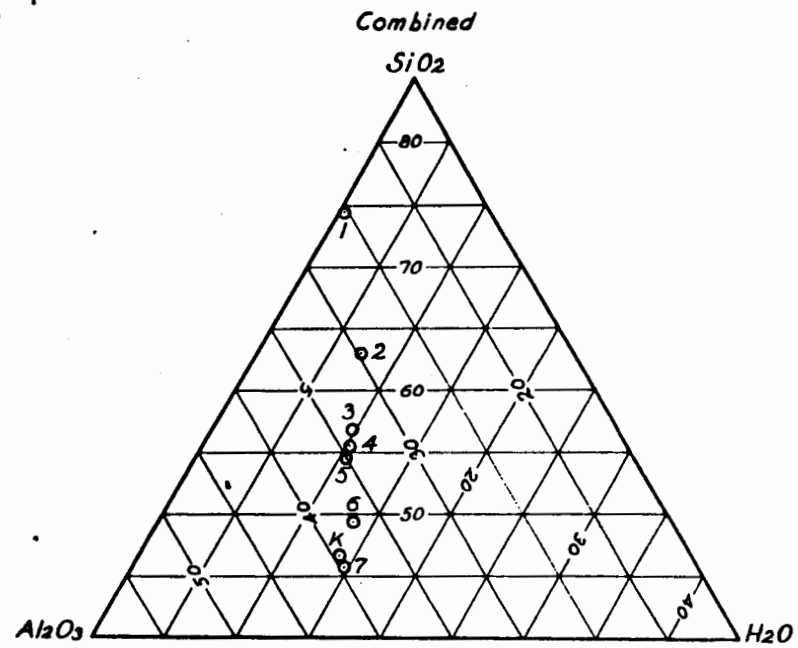

FIG. 7.—Diagram showing gradation from unweathered aluminum silicates in gneiss (1) to kaolinite (*K*) in residual clay samples (2–7).

Kaolinization diagram.—The progress of the decomposition of the silicates to kaolinite is shown in Figure 7. This diagram is similar to one used by Mead[16] to represent the gradation from syenite to bauxite in the Arkansas deposits. In the present study it was found that plotting the percentages of silica, alumina, and combined water was ineffective in showing the extent of alteration because the quartz contributes heavily to the total silica of the clays, masking the constituents of interest which are combined silica, alumina, and com-

[16] W. J. Mead, "Occurrence and Origin of the Bauxite Deposits of Arkansas," *Econ. Geol.*, Vol. X (1915), p. 49.

bined water. The quartz percentages (Table 2), therefore, were subtracted from the figures for silica to obtain the percentages of combined silica. The combined silica, the alumina, and the combined water were recalculated to 100 and plotted with the result that the series of samples shows a progression toward the theoretical composition of kaolinite.

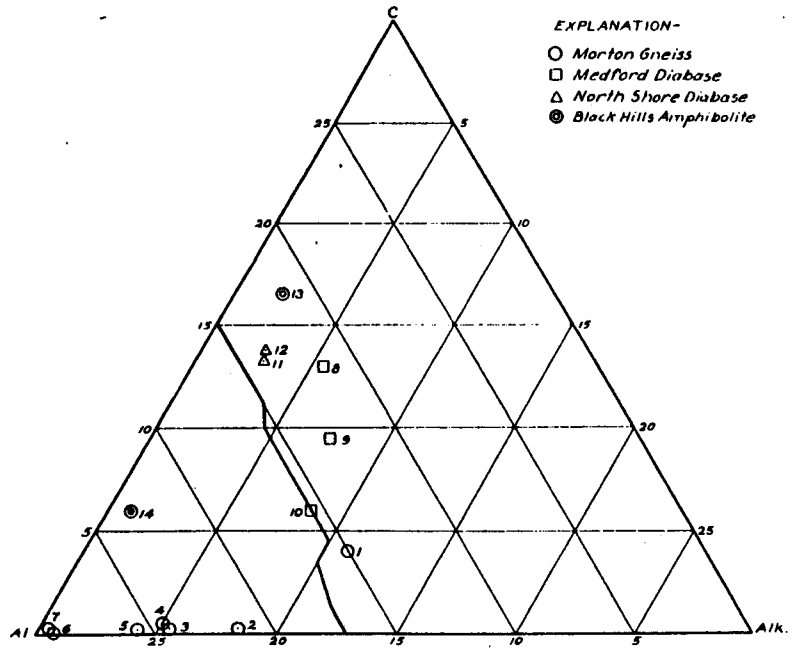

FIG. 8.—Fresh and weathered rocks plotted on the *Al-C-Alk* diagram (after Osann). Rocks with sedimentary characteristics fall to the left of the heavy line; igneous rocks, to the right.

Sample No. 7 falls beyond the point representing kaolinite, indicating an excess of alumina and water. This may be caused by errors in the analytical determinations or in the estimation of quartz, or it may indicate the presence of an aluminous hydrate. Grout[17] records a test by Bowles indicating 3–4 per cent of bauxite in some of the clays of this area. The clays tested by Bowles, however, were taken from the overlying Cretaceous deposits and show a concretionary texture. None of the residual clays sampled exhibited this texture.

[17] *Op. cit.*, p. 219.

An excess of water may be explained by the presence of hydrated oxides of iron.

"Al-C-Alk" diagram.—The rapid impoverishment in lime and in soda and the more gradual loss of potash are the most striking features of the decomposition of the gneiss. The progress of the alteration is well displayed in the *Al-C-Alk* diagram of Figure 8. In this figure the co-ordinates are Al_2O_3, CaO + BaO, and $Na_2O + K_2O$. The *Al* corner of the triangle, therefore, would correspond to kaolinite.

DISCUSSION AND SUMMARY

Certain discrepancies or irregularities, both in chemical and in mineralogical data obtained in the study of the fresh granite gneiss and of its residual weathering products, are undoubtedly the result of differences in parent-material. These differences have been partly smoothed out in the curves of Figure 6 and in the diagram of Figure 7. If the data are generalized in this manner, the picture of the weathering processes in the Morton-Redwood Falls area is believed to be fairly accurate.

Besides differences in parent-rock which might be reflected in the composition of the residual clays, other factors tend to complicate the data. The formation or the introduction of secondary heavy minerals, such as siderite, affects the percentages of the original minerals in the heavy concentrates. However, it will be noted (Table 4) that zircon constitutes a larger percentage of the total heavy minerals in the clay samples than in the fresh rock. The obvious conclusion is that the heavy minerals of the gneiss have been largely destroyed, and those minerals remaining represent in some degree the relative resistance or stability of the minerals. Of the heavy minerals, hornblende, epidote, titanite, and apatite appear to be least stable. Ilmenite-magnetite seems to be more resistant, and zircon, most stable. Even the zircon, however, shows signs of attack in its dusty, granular appearance. The altered mineral is brown, has a lower birefringence than fresh zircon, and tends to become opaque.

If alumina is considered constant, the constituents lost, in order of rate of loss, are Na_2O, CaO, MgO, K_2O, BaO, P_2O_5, SiO_2, S, and FeO. Those gained are H_2O, CO_2, Fe_2O_3, TiO_2, Fe, and MnO.

The following order of stability is suggested for the original minerals of the gneiss:

Plagioclase, epidote, hornblende, titanite, apatite	Least stable
Ilmenite-magnetite, Biotite, Microcline, orthoclase	Moderately stable
Zircon, quartz	Most stable

The abundant minerals in the residual clays are kaolinite and quartz. The absolute behavior of the quartz during weathering is not certain, but, after liberal allowances have been made for possible differences in parent-rock and for errors inherent in the technique, it appears that some of the quartz has been removed by solution. Ross and Kerr[18] cite examples of the replacement of quartz by kaolinite.

THE MEDFORD DIABASE

GENERAL STATEMENT

The Medford diabase in eastern Massachusetts has afforded material for a number of investigations primarily concerned with the weathering of this rock. Probably the best known is the classical study by Merrill.[19]

More recent papers are concerned with the time of weathering. Wolf[20] and Lane[21] hold that the weathering is mainly older than the Wisconsin glaciation as has been suggested by Wilson.[22] Billings and Roy[23] believe that the weathering is younger than the last ice inva-

[18] C. S. Ross and P. F. Kerr, "The Kaolin Minerals," *U.S. Geol. Surv. Prof. Paper 165-E* (1931), p. 174.

[19] G. P. Merrill, "Disintegration and Decomposition of Diabase at Medford, Massachusetts," *Geol. Soc. Amer. Bull. 7* (1896), pp. 349–62; *Rocks, Rock-weathering, and Soils* (New York: Macmillan Co., 1913), pp. 198–203.

[20] Arthur Wolf, "Weathering of the Medford Diabase—Pre- or Postglacial?" *Jour. Geol.*, Vol. XL (1932), pp. 459–66.

[21] A. C. Lane and Arthur Wolf, "Reply to Discussion of 'Weathering of the Medford Diabase—Pre- or Postglacial?'" *Jour. Geol.*, Vol. XLI (1933), pp. 661–66.

[22] A. W. G. Wilson, "The Medford Dike Area," *Boston Soc. Nat. Hist.*, Vol. XXX (1901), pp. 353–74.

[23] M. P. Billings and C. J. Roy, "Weathering of the Medford Diabase—Pre- or Postglacial?" *Jour. Geol.*, Vol. XLI (1933), pp. 654–61.

sion. They are supported by the earlier work of Crosby,[24] of Barton,[25] and of Merrill.[26] In this paper new chemical data obtained on a series of samples generously supplied by Dr. A. C. Lane are presented. Descriptions of sample locations are given in Table 7.

PETROGRAPHY

Petrographic descriptions of the Medford diabase have been given by Hobbs,[27] by Jaggar,[28] and by Lane.[29] The notes which follow were made from study of thin sections of fresh rock No. 9. Plagioclase, hornblende, augite, magnetite, biotite, and apatite are the

TABLE 7

LOCATIONS OF SAMPLES AS RECEIVED FROM A. C. LANE

Sample No.	Lane's No.	Description
8	.....	Fresh Medford diabase from an abandoned quarry
9	.7562	Relatively fresh diabase. Opposite 93 Governor's Ave., Medford, Mass. Lat. 42°25′; Long. 71°6′54″
10	.7561	Weathered Medford diabase. Four feet from surface in disintegrating crack. Location as of sample No. 9
7558	.7558	Decayed diabase, Cousens Gymnasium, Tufts College
7559	.7559	Glacial till overlying .7558. Cousens Gymnasium, Tufts College
7560	.7560	Residual boulder of diabase. Cousens Gymnasium, Tufts College

essential minerals. Quartz, orthoclase, epidote, chlorite, calcite, and pyrite make up the rest of the rock. The plagioclase is zoned labradorite partly replaced by orthoclase and by intergrowths of orthoclase and quartz. The plagioclase has been much altered, and individual crystals have been completely changed to a felt of sericite

[24] W. O. Crosby, "Contributions to the Geology of Eastern Massachusetts," *Boston Soc. Nat. Hist.*, Vol. III (1880).

[25] G. H. Barton, "Bowlders Formed *in Situ*," *Tech. Quarter.*, Vol. V (1892), pp. 401–5.

[26] "Disintegration and Decomposition of Diabase at Medford, Massachusetts," *loc. cit.*, p. 358.

[27] W. H. Hobbs, "On the Petrographical Characters of a Dike of Diabase in the Boston Basin," *Mus. Comp. Zoöl. Bull. 16* (1888), pp. 1–13.

[28] T. A. Jaggar, "An Occurrence of Acid Pegmatyte in Diabase," *Amer. Geol.*, Vol. XXI (1898), pp. 203–13.

[29] A. C. Lane, "Die Korngrösse der Auvergnosen," *Rosenbusch-Festschrift* (1906).

fibers. Pyroxene is altered to hornblende. Reddish-brown biotite forms rims around grains of magnetite. Apatite, which is rather

TABLE 8

CHEMICAL ANALYSES OF FRESH AND WEATHERED DIABASE FROM MEDFORD, MASSACHUSETTS

	Analyst								
	S. S. Goldich (1935)			C. N. Whitney (1911)*			G. P. Merrill (1896)†		R. C. Sweetser (1887)‡
	Fresh		Weathered	Fresh	Weathered		Fresh	Weathered	Fresh
	8	9	10	6	5	2	1	3	
SiO_2	47.59	51.44	51.38	50.30	49.02	50.58	47.28	44.44	48.75
Al_2O_3	14.78	15.67	15.92	17.32	19.11	17.93	20.22	23.19	17.97
Fe_2O_3	4.39	2.25	10.92	4.07	8.74	8.87	3.66	12.70	0.41
FeO	9.11	8.37	2.60	10.65	6.30	5.46	8.89	.....	13.62
MgO	4.28	2.09	1.26	3.94	3.05	2.56	3.17	2.82	3.39
CaO	9.06	6.31	3.52	5.25	4.66	3.27	7.09	6.03	8.82
Na_2O	3.36	4.42	4.16	3.96	4.07	4.55	3.94	3.93	1.63
K_2O	1.18	1.91	1.57	1.54	1.02	1.21	2.16	1.75	2.40
H_2O+	1.35	1.67	2.94	1.69	3.26	2.95	2.73§	3.73§	0.60
H_2O-	.24	0.41	1.70	.....	.....	.....	.....	.....	.....
TiO_2	3.55	1.95	2.52	n.d.	n.d.	n.d.	n.d.	n.d.	0.99
P_2O_5	0.42	0.97	1.03	0.20	0.54	0.70	0.68	0.70	0.68
MnO	0.17	0.18	0.22	0.61	0.45	0.37	0.77	0.52	0.91
CO_2	0.65	2.14	0.07	0.37	None	None	.....	.....	Tr.
S	0.13	0.12	0.01	Tr.	None	None	.....	.....	Tr.‖
Cl	.....	.....	.....	Tr.	Tr.	Tr.	.....	.....	.....
	100	99.90	99.82	99.90	101.22¶	98.45	100.59	99.81	100.17
Less O=S	0.05	0.05	.....	.....	.....	.....	.....	.....	.....
Total	100.21	99.85	99.82	99.90	100.22	98.45	100.59	99.81	100.17
Sp. gr.	2.945	2.80	2.749	2.87	2.74	.....	.....	.....	2.985

* Published by Arthur Wolf, *Jour. Geol.*, Vol. XL (1932), p. 460.
† *Geol. Soc. Amer. Bull.* 7 (1896), p. 353.
‡ Published by W. H. Hobbs, *Mus. Comp. Zool. Bull.* 16 (1888), p. 9.
§ Loss on ignition.
‖ FeS₂.
¶ Whitney's error in summation.

abundant, appears to be corroded. The changes noted are probably in part deuteric, but the sericite, chlorite, calcite, and pyrite are hydrothermal.

CHEMICAL ANALYSES

Chemical analyses of three of the samples collected by Lane are given in Table 8. The published analyses of fresh and weathered diabase are also included. Of the new analyses, samples No. 9 and No. 10 are from the same locality as Whitney's[30] material (Nos. 6, 5, 2). Sample No. 8 represents a more basic facies of the diabase and seems to be much like the material studied by Merrill. Samples No. 8 and No. 9 reveal differences in the Medford diabase, a fact known and referred to by previous writers. When classified in the C.I.P.W. system, these samples fall in different classes (Table 9).

TABLE 9

	Sample No. 8	Sample No. 9
Class:	(II) III, salfemic	II (III), dosalic
Subclass:	1	1
Order:	5, perfelic	5, perfelic
Rang:	3, alkalicalcic	2, domalkalic
Subrang:	4, dosodic	4, dosodic
Name:	CAMPTONOSE	AKEROSE

Assuming alumina to have remained constant, Merrill calculated the percentage of each constituent lost during weathering. Billings and Roy made similar calculations using Whitney's analyses, and the writer has done the same for analyses No. 9 and No. 10. Inasmuch as the quality of the published analyses[31] has been mentioned by Billings, Roy, Lane, and Wolf, it is of interest to compare the calculations based on the new and old chemical analyses (Table 10).

The most obvious inconsistency in the data of Table 10 is in the figures for manganous oxide. A loss of 40 per cent of the MnO is indicated by the older analyses, but the new data show a gain for this constituent. Procedures formerly used in the determination of MnO commonly resulted in large positive errors. The modern colorimetric method using potassium periodate as the oxidizing agent is effective and leaves little to be desired for accuracy. Disregarding MnO, the calculated percentage losses are fairly consistent, and differences in samples of the weathered as well as of the fresh diabase may account for some of the discrepancies.

[30] C. N. Whitney, "The Medford Diabase Dike" (Tufts College thesis [1911]).

[31] The analyses by Sweetser and Merrill are rated as inferior by Washington, "Chemical Analyses of Igneous Rocks," *U.S. Geol. Surv. Prof. Paper 99* (1917), p. 1065.

The relative gains and losses based on analyses No. 9 and No. 10 are shown in the "straight-line" diagram, Figure 9. Samples 8, 9, and 10 have been plotted on the *Al-C-Alk* diagram (Fig. 6). Differences in the fresh rock can be seen in the positions of samples No. 8 and No. 9. The changes effected by weathering are shown by the differences in the positions of weathered sample No. 10 and the fresh rock No. 9. The weathered diabase is on the boundary line as drawn by Osann to differentiate sedimentary from igneous rocks.

TABLE 10

PERCENTAGE OF EACH CONSTITUENT LOST IN WEATHERING OF MEDFORD DIABASE

(Alumina Considered Constant)

	A	B	C	D
SiO_2	18.03	11.74	2.88	1.68
Al_2O_3	0.00	0.00	0.00	0.00
Fe_2O_3	18.10	Gain	Gain	Gain
FeO		46.42	50.48	69.42
MgO	21.70	29.89	37.26	39.28
CaO	25.89	19.61	39.87	45.09
Na_2O	12.83	6.90	Gain	7.38
K_2O	29.15	40.01	24.10	19.09
H_2O+	Gain	Gain	Gain	Gain
H_2O-				
TiO_2	n.d.	n.d.	n.d.	Gain
P_2O_5	11.39	Gain	Gain	Gain
MnO	41.57	33.19	41.41	Gain
CO_2	n.d.	n.d.	n.d.	96.78
S	n.d.	n.d.	n.d.	92.80

A. Fresh and weathered by G. P. Merrill.
B. Fresh rock No. 6 and weathered rock No. 5, by C. N. Whitney.
C. Fresh rock No. 6 and weathered rock No. 2, by C. N. Whitney.
D. Fresh rock No. 9 and weathered rock No. 10, by S. S. Goldich.

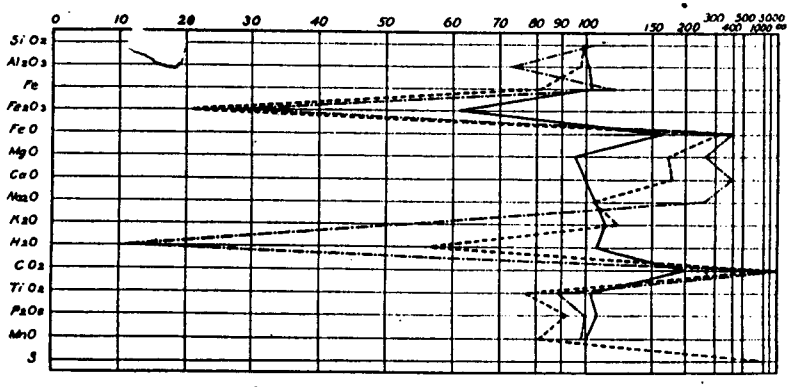

FIG. 9.—Representing the losses and gains of constituents by weathering of Medford diabase (dash line), North Shore diabase (solid line), and Black Hills amphibolite (dot-dash line).

HEAVY-MINERAL ANALYSES

The heavy minerals of the fresh and weathered diabase were separated, and the approximate percentages of the minerals in the heavy fractions of the washed samples are given in Table 11. An absolute loss in the heavy minerals as a result of weathering is indicated. The relative abundance of the heavy minerals in fresh and weathered diabase suggests also that the rate of decomposition is different for the various minerals. The order of stability, from least to most stable, appears to be chlorite, pyroxene, epidote, hornblende, biotite, apatite, magnetite-ilmenite.

DISCUSSION AND SUMMARY

It is not proposed to settle the question of the time of weathering of the Medford diabase in this paper. However, some of the data may be pertinent to the problem. In Table 12 ferrous and ferric iron determinations on the samples comprising the series received from A. C. Lane are given. As oxidation of the ferrous iron is characteristic of the weathering of the diabase, the percentages of the total iron in the bivalent (Fe^{++}) and in the trivalent (Fe^{+++}) states have been computed.

In the fresh diabase from 70 to 80 per cent of the total iron is bivalent. This range will include earlier analyses not shown in Table 12. In samples of weathered diabase, depending on the degree of alteration, a smaller fraction of the total iron is ferrous—from 20 to 68 per cent. In the sample of glacial till 59.4 per cent of the total iron is bivalent, but in weathered diabase immediately below this till only 37.5 per cent of the total iron is bivalent. It is not known what percentage of the iron was bivalent in the original fresh till, but it is most unlikely that it was as high as that of the diabase.

If it is assumed that the rate of oxidation of ferrous iron in the till and in the diabase is about the same, there has been less oxidation

(weathering?) of the till than of the diabase. This conclusion would be in accord with the hypothesis of preglacial weathering. The assumption of the rate of oxidation, however, may not be justified.

TABLE 11

HEAVY-MINERAL ANALYSES

	Sample No. 9 (Fresh)	Sample No. 10 (Weathered)
	Percentage weight	
Loss on washing	17.2	21.4
Heavy minerals in washed sample	22.5	15.9
	Percentage approximate weight of total heavy minerals	
Mineral:		
Hornblende	36.0	23.0
Chlorite	18.0	0.28
Biotite	14.0	9.4
Magnetite, Ilmenite	12.0	24.0
Augite	10.0	3.1
Apatite	7.7	10.0
Epidote	1.3	0.51
Secondary iron oxides and leucoxene	0.90	29.0
Pyrite	0.22	0.08
Unknown	0.47	0.12

It is also true that some minerals containing ferrous iron are more stable than others, and possibly the minerals of the till are less susceptible to weathering than those of the diabase. On the other hand, permeability may be an important factor, favoring a higher rate of oxidation for the glacial till.

A single chemical criterion cannot always be applied safely, especially one requiring somewhat uncertain assumptions. The data, however, do indicate that considerable decomposition, involving oxidation and solution, has taken place locally, at least, in the weathering of the diabase. The extent of this decomposition will be referred to again in the following section dealing with the weathering of a similar rock.

TABLE 12

FERROUS AND FERRIC IRON IN SAMPLES OF MEDFORD DIABASE AND IN GLACIAL TILL

	8	9	10	.7558	.7559	.7560
Total iron (as Fe_2O_3)	14.51	11.55	13.81	12.04	5.61	12.05
Fe_2O_3	4.39	2.25	10.92	7.53	2.28	4.61
FeO	9.11	8.37	2.60	4.06	3.00	6.69
	Percentage of Fe^{++} and Fe^{+++} of total Fe					
Fe^{++}	69.8	80.5	20.9	37.5	59.4	61.7
Fe^{+++}	30.2	19.5	79.1	62.5	40.6	38.3

8 Fresh Medford diabase, from abandoned quarry.
9 Relatively fresh diabase, opposite 93 Governor's Ave., Medford, Mass.
10 Weathered diabase, opposite 93 Governor's Ave., Medford, Mass.
.7558. Weathered diabase, Cousens Gymnasium, Tufts College.
.7559 Glacial till overlying .7558.
.7560. Residual boulder of diabase, Cousens Gymnasium, Tufts College.

DIABASE ON THE NORTH SHORE OF LAKE SUPERIOR

GENERAL STATEMENT

Diabase Hill is situated about 7 miles northeast of Two Harbors opposite Encampment Island in Lake Superior. The diabase from which the hill is named is deeply weathered, and on the northern side considerable material has been taken out with a steam shovel for use as road metal. Brief mention of the weathering of this rock is made by Schwartz[32] and in an earlier work by Irving.[33]

[32] G. M. Schwartz, "A Guidebook to Minnesota Trunk Highway No. 1," *Minn. Geol. Surv. Bull. 20* (1925), p. 71.

[33] R. D. Irving, "The Copper-bearing Rocks of Lake Superior," *U.S. Geol. Surv. Mon. 5* (1883), p. 286.

A portion of Diabase Hill was blasted out in the construction of the highway, exposing the unaltered rock which is fine to medium in grain. Green feldspar and magnetite are the only minerals readily visible in hand specimens. The diabase weathers to a nodular or pebbly coarse, yellowish to reddish-brown sand. The larger lumps generally have a core of comparatively fresh diabase. Sample No. 11 represents the fresh rock. Sample No. 12 was taken from the weathered material about 35 feet above the fresh sample.

TABLE 13

CHEMICAL ANALYSES OF FRESH AND WEATHERED DIABASE FROM NORTH SHORE, LAKE SUPERIOR

	11	12
SiO_2	46.88	46.91
Al_2O_3	20.98	20.27
Fe_2O_3	3.32	5.30
FeO	5.56	3.44
MgO	4.74	4.89
CaO	11.15	11.19
Na_2O	2.49	2.31
K_2O	0.29	0.25
H_2O+	1.45	1.35
H_2O-	1.59	2.52
CO_2	0.12	0.06
TiO_2	1.11	1.08
P_2O_5	0.15	0.14
MnO	0.12	0.12
S	0.02	0.02
Total	99.97	99.85
Sp. gr. $t°/4°$	2.791	2.756

11. Fresh diabase.
12. Weathered diabase. S. S. Goldich, analyst.

PETROGRAPHY

The fabric of the rock is diabasic and porphyritic. The primary essential minerals are plagioclase, augite, and magnetite-ilmenite. The plagioclase is zoned, and inclusions of magnetite and pyroxene are numerous in the outer margins. The central, more basic portions have a maximum symmetrical extinction angle of 38°, indicating $Ab_{32}An_{68}$. The presence of serpentine in the characteristic forms resulting from the alteration of olivine indicates that the latter was

an original mineral, though none was noted in thin sections. Other minerals, deuteric or hydrothermal rather than weathered, include biotite, uralite, chlorite, pyrite, and zeolite(?).

CHEMICAL ANALYSES

Chemical analyses of fresh and weathered rock (Table 13) are remarkably similar. The significant differences are in moisture content and in the proportions of ferrous and ferric oxides.

TABLE 14

HEAVY-MINERAL ANALYSES

	Sample No. 11 (Fresh)	Sample No. 12 (Weathered)
	Percentage weight	
Loss on washing	20.4	11.6
Heavy minerals in washed sample	24.5	23.7
	Percentage approximate weight of total heavy minerals	
Mineral:		
Pyroxene	78.0	74.0
Magnetite, Ilmenite	19.0	24.0
Biotite, Chlorite	2.5	0.90
Pyrite	0.15	0.15
Amphibole	0.10	0.04
Apatite	0.02	0.02

HEAVY-MINERAL ANALYSES

The fresh diabase and its residual weathering products were ground to pass a 60-mesh sieve, and the washed samples were subjected to the heavy-mineral technique. The mineralogical analyses of Table 14 suggest a slight concentration of magnetite and ilmenite

at the expense of pyroxene, but the differences are not great and approach the limits of accuracy of the method.

SUMMARY

The weathering of the diabase in northern Minnesota has not produced profound mineralogical changes. As in the case of the diabase from Medford, there was notable oxidation of the ferrous iron. The depth of weathering in both areas reaches to some 40 feet locally, but the significant feature is the fact that decomposition was important in the Medford occurrence and of slight importance in the weathering of the Minnesota rock.

The amount of decomposition suffered by the diabase in northern Minnesota is what the writer would expect as a postglacial effect in that region. It is believed that in the early stages of weathering, a small amount of chemical action is effective in bringing about a striking loss in coherence and a pronounced discoloration. The results of this stage of weathering are deceptive as has been demonstrated by Blackwelder.[34]

BLACK HILLS AMPHIBOLITE

GENERAL STATEMENT

A cut on the Northwestern Railroad track exposes amphibolite which occurs as a lens in a fine-grained sericite schist about ¼ mile northeast of Lead, South Dakota. The fresh rock grades upward through a weathered zone 15 feet thick, passing into soil. The outcrop is about 50 feet long and 20 feet wide. Samples No. 13, representing the fresh rock, and No. 14, the residual material, were collected by Dr. G. M. Schwartz, of the University of Minnesota.

The fresh phase is a massive, coarsely crystalline rock composed largely of dark-green hornblende. It weathers to a yellowish-brown silt containing coarse material up to about the size of gravel. The larger fragments on being broken display a fibrous structure and green color.

PETROGRAPHY

The amphibolite is composed chiefly of hornblende. Garnet, titanite, quartz, chlorite, calcite, pyrite, and a black opaque mineral,

[34] Eliot Blackwelder, "Exfoliation as a Phase of Rock Weathering," *Jour. Geol.*, Vol. XXXIII (1925), pp. 793–806.

possibly ilmenite, constitute about 25 per cent of the rock. The texture is apparently a recrystallized one, and the large metacrysts of hornblende include numerous small grains of other minerals. A linear arrangement of the small anhedral grains of quartz and ilmenite is particularly striking. The thin bands of the black opaque mineral are conspicuous in thin section and appear to be entirely independent of the minerals in which they are contained. The arrangement suggests a texture inherited from a pre-existing rock, possibly a schist (Fig. 10).

FIG. 10.—Parallel bands of ilmenite in Black Hills amphibolite suggesting a pre-existing structure independent of the present hornblende (*H*), garnet (*G*), and calcite (*C*). Some sections show a similar arrangement of small quartz (*Q*) grains. Ordinary light. ×30.

CHEMICAL ANALYSES

Chemical analyses of the fresh and weathered amphibolite are given in Table 15. The high FeO, MnO, TiO_2, and CO_2 content of the fresh rock are noteworthy. In the residual material, the abundance of water (13 per cent) is striking. Of the total water, more than half is lost on drying the sample below 110° C. This water is apparently adsorbed water. It is regained on allowing the dried sample to stand exposed to the air of the laboratory.

The relative gains and losses resulting from the weathering of this

ck are shown in Figure 9. The values plotted in this figure are based on analyses in Table 15. If the chemical data were recalculated on a moisture-free basis, 20 rather than 11 grams of the weathered rock would be required to furnish the water present in 100 grams of fresh amphibolite. The points on the diagram representing other constituents, excepting CO_2, would be shifted in the opposite direction.

TABLE 15

CHEMICAL ANALYSES OF FRESH AND WEATHERED AMPHIBOLITE FROM BLACK HILLS

	13	14
SiO_2	41.98	40.15
Al_2O_3	13.99	19.52
Fe_2O_3	2.22	11.97
FeO	15.64	3.95
MgO	5.45	2.09
CaO	10.91	2.73
Na_2O	1.23	0.45
K_2O	0.18	0.33
H_2O+	1.37	6.25
H_2O-	0.12	6.94
CO_2	1.43	0.00
TiO_2	3.84	4.34
P_2O_5	0.36	0.36
MnO	1.03	1.06
BaO	0.00	n.d.
S	0.07	n.d.
Total	99.82	100.14
Sp. gr. $t°/4°$	3.239	2.684

13. Fresh amphibolite.
14. Weathered amphibolite. S. S. Goldich, analyst.

If alumina is considered constant, the constituents lost, in order of decreasing percentage of loss, are CO_2, CaO, FeO, Na_2O, MgO, Fe, SiO_2, P_2O_5, MnO, and TiO_2. Those gained include H_2O, Fe_2O_3, and K_2O. Iron rather than alumina has been considered the invariable constituent in calculations of gains and losses of some occurrences.[35] On this basis, the constituents lost are CO_2, CaO, FeO, Na_2O, and MgO. Those gained are H_2O, Fe_2O_3, K_2O, Al_2O_3, TiO_2, MnO, P_2O_5, and SiO_2, water being greatest, and silica least.

[35] Merrill, *Rocks, Rock-weathering, and Soils*, p. 187.

The fresh amphibolite and its residual weathering products have been plotted on the *Al-C-Alk* diagram (Fig. 8). The pronounced chemical changes resulting from the decomposition of the rock can be seen in the positions of samples No. 14 and No. 13.

The position of the fresh sample in the "igneous rock field" might lend support to Paige's[36] contention that the amphibolites of this region were derived from igneous rocks. However, Runner,[37] although admitting the composition of the amphibolites approaches that of basic igneous rocks, holds, on the basis of field evidence, that they are of sedimentary derivation. He believes that calcareous, magnesian, and ferruginous shales by recrystallization under pressure yielded the amphibolites. The intrusive relationships of the dikelike masses in the schist country rock are said to be due to plastic flow under pressure without fusion of the rock minerals.

HEAVY-MINERAL ANALYSES

Samples of the fresh and weathered amphibolite were ground to pass a 60-mesh sieve. The washed samples were separated with bromoform, and the approximate weight percentages of the minerals in the heavy fractions are given in Table 16. The amount of heavy minerals obtained from the residual material is considerably less than that from the fresh amphibolite, and the relative abundance of the minerals is very different. This change is the result of the decomposition of the hornblende, which makes up 77 per cent of the heavy minerals of the fresh rock as opposed to about 7 per cent for the weathered material.

The light-mineral fraction from the fresh amphibolite was quartz and calcite. Quartz but no calcite was found in the light fraction of the weathered phase. This fraction was flooded with the alteration products of the hornblende, which range from colorless plates and fibers to yellowish and brownish material. The color and the general opacity of this material are largely caused by the secondary iron oxides coating the grains or in intimate intergrowths. The alteration products have a rather wide range of refractive indices. Limiting values determined on almost colorless fibers are, approximately,

[36] N. H. Darton and Sidney Paige, "Central Black Hills, South Dakota," *U.S. Geol. Surv. Folio 219* (1925), p. 4.

[37] J. J. Runner, "Intrusive Sedimentary Amphibolites" (Abst.), *Prelim. List of Titles and Abstracts, 49th Annual Meeting, Geol. Soc. Amer.* (1936), p. 42.

alpha = 1.518 and gamma = 1.550, corresponding to beidellite in the clay minerals.

TABLE 16

HEAVY-MINERAL ANALYSES

	Sample No. 13 (Fresh)	Sample No. 14 (Weathered)
	Percentage weight	
Loss on washing	14.4	30.8
Heavy minerals in washed sample	91.9	30.7
	Percentage approximate weight of total heavy minerals	
Mineral:		
Hornblende	77.0	6.7
Black opaque mineral (Ilmenite?)	14.0	18.0
Garnet	5.6	45.0
Chlorite	2.2	3.4
Leucoxene	0.72	n.d.
Epidote	0.47	0.02
Apatite	0.39	0.54
Titanite	0.03	0.03
Pyrite	0.01	0.01
Altered hornblende	.....	26.0*
Unknown	.....	0.14

* Contains leucoxene and secondary iron oxides.

According to Ross and Kerr,[38] beidellite or a related clay mineral may be formed by the alteration of ferromagnesian minerals. They state that a brownish color in thin section may indicate ferric iron or the nontronite molecule.

[38] C. S. Ross and P. F. Kerr, "The Clay Minerals and Their Identity," *Jour. Sed. Petrol.*, Vol. I (1931), p. 62.

The moisture content of sample No. 14 is suggestive of the behavior of minerals in the montmorillonite-beidellite group, which characteristically adsorb water. After assigning oxides to calcite, quartz, garnet, and chlorite in amounts estimated from thin section and heavy separates, there is evidence that the hornblende has alumina enough to make beidellite a probable product.

SUMMARY

Oxidation, hydration, and solution were all active in the decomposition of the Black Hills amphibolite.

Study of the minerals in the fresh and weathered phases shows the complete removal of calcite and the severe alteration of hornblende to beidellite or related clay minerals. Garnet has resisted the alteration as is indicated by its concentration in the heavy mineral fraction of the weathered rock.

Although the *Al-C-Alk* diagram clearly brings out the chemical changes effected by weathering with the development of "sedimentary" chemical characteristics in the weathered phase, it is not certain that the diagram differentiates all para- from orthometamorphic rocks.

DISCUSSION OF PRINCIPLES

PREVIOUS WORK

In view of the great number of contributions which have swelled the literature pertaining to weathering, it is indeed fortunate that a number of compilations and treatises summarizing the processes and results of weathering are available. The works of Van Hise,[39] Steidtmann,[40] Merrill,[41] Leith and Mead,[42] Clarke,[43] Twenhofel,[44] and others are well known and readily available. The writer has attempted to correlate the findings of the present study with the conclusions reached by these men.

[39] C. R. Van Hise, "A Treatise on Metamorphism," *U.S. Geol. Surv. Mon. 47* (1904).

[40] Edward Steidtmann, "A Graphic Comparison of the Alteration of Rocks by Weathering with Their Alteration by Hot Solutions," *Econ. Geol.*, Vol. III (1908), pp. 382–410.

[41] *A Treatise on Rocks, Rock-weathering, and Soils.* [42] *Op. cit.*

[43] F. W. Clarke, "Data of Geochemistry," *U.S. Geol. Surv. Bull. 770* (1924), pp. 679–543.

[44] W. T. Twenhofel and collaborators, *Treatise on Sedimentation* (2d ed.; Baltimore: Williams & Wilkins Co., 1932), pp. 1–21.

CHEMICAL CHANGES

The rate of rock decomposition depends upon a number of variable factors. Climate and rock composition are the most important, but other conditions also require consideration in studies of individual rocks. The climatic control of weathering is emphasized by soil workers, but attempts to estimate climatic conditions of past geological time from weathering products have not met with any great degree of success. The geologist must content himself largely with the study of the changes that can be measured in the rock materials.

Students of weathering have concluded that all constituents, excepting water, are lost in prolonged chemical action. Direct comparison of chemical analyses fails to give an accurate understanding of the changes produced by weathering. Analyses of fresh and weathered material must be reduced to a common basis. The consensus of opinion is that of the common rock constituents, alumina and iron are least affected.

TABLE 17

ORDER OF THE RATES OF LOSS OF CHEMICAL CONSTITUENTS ASSUMING ALUMINA CONSTANT

	Morton Gneiss	Medford Diabase	*Black Hills Amphibolite
1	Na_2O	CaO	CaO
2	CaO	MgO	Na_2O
3	MgO	K_2O	MgO
4	K_2O	Na_2O	Fe
5	SiO_2	SiO_2	SiO_2
	Al_2O_3	Al_2O_3	Al_2O_3
	Fe (gain)	Fe (gain)	K_2O (gain)
	H_2O (gain)	H_2O (gain)	H_2O (gain)

Steidtmann[45] concluded that the order in which the constituents are lost is lime, magnesia, soda, potash, silica, iron, and alumina. This sequence is approximately that found by other writers. The order given by Leith and Mead[46] for acid igneous rocks is lime, soda, magnesia, potash, silica, iron, and alumina.

In Table 17 the order of the rates of loss of the important constituents is given for the three rocks studied in which decomposition has been important. As is indicated by the similarity of the chemical

[45] *Op. cit.*, p. 406.

[46] *Op. cit.*, pp. 16–17.

changes noted by many investigators, the processes of weathering operate with appreciable uniformity.

STABILITY OF ROCK-FORMING MINERALS

A corollary of the concept of an order for the rates at which chemical constituents are lost in rock-weathering is that the rock-forming minerals exhibit different degrees of stability. This second concept in its broader implications is undenied. In the present study the relative stability of the original minerals has been suggested. It would seem desirable to state some order of stability applicable to the common igneous rock-forming minerals in general; and the consistency of the findings, observed and experimental, which have been reported in the literature[47] is favorable to the idea that some such order does exist.

To the list of minerals encountered in this study a few additional minerals on which numerous observations have been made can be added. It is generally agreed that olivine yields readily to weathering and that the rate of attack of this mineral exceeds that of any of the other common ferromagnesian silicates. Augite, relatively more stable than olivine, decomposes more readily than hornblende, which in turn is less stable than biotite. Potash feldspars are more resistant than the soda-lime feldspars, and sodic plagioclase is more durable than calcic plagioclase. Of the aluminum silicates comprising the essential minerals of the common igneous rocks, muscovite appears to be most resistant to decomposition.

As a group, the mafic minerals are less stable than the salic minerals. For this reason, and for others, as will become apparent, the rock minerals have been arranged in two series in order of increasing stability in Table 18. To the petrologist it is at once evident that the arrangement in the table is that of the reaction series as presented by Bowen.[48] The table, however, is not to be interpreted in the manner of the reaction series. It is not to be inferred that olivine weathers to pyroxene but rather that, in a normal igneous rock containing olivine and pyroxene, the rate of decomposition of the olivine may

[47] Good summaries are those of Clarke, *op. cit.*, pp. 481–94; and P. G. H. Boswell, *On the Mineralogy of Sedimentary Rocks* (London: Murby & Co., 1933), pp. 37–47.

[48] N. L. Bowen, "The Reaction Principle in Petrogenesis," *Jour. Geol.*, Vol. XXX (1922), pp. 177–98.

be expected to exceed that of the pyroxene. Similarly, all other things being equal, the rate of decomposition of gabbro will exceed that of granite. This concept is here called, by analogy with the reaction principle, the *stability principle.*

The coincidence between the arrangement in Table 18 and the reaction series is certainly more than fortuitous. The reaction series indicates stability of the minerals under conditions of equilibrium of composition, pressure, and temperature which prevail at the time of formation of the igneous rock-forming minerals. These conditions are markedly different from surface conditions; for this reason, min-

TABLE 18

MINERAL-STABILITY SERIES IN WEATHERING

Olivine

Augite

Calcic plagioclase

Hornblende

Calci-alkalic plagioclase

Alkali-calcic plagioclase

Alkalic plagioclase

Biotite

Potash feldspar

Muscovite

Quartz

erals weather. Perhaps the differential between equilibrium conditions at the time of formation and those existing at the surface governs the order of stability.

The stability principle is a generalization from accumulated data. Because of the variety of conditions and agents of weathering, exceptions may be expected. The writer believes that such exceptions, rather than disproving the validity of the principle, indicate that unusual conditions attended the weathering. Careful study should be made to ascertain these conditions.

CHEMICAL CONSIDERATIONS

Chemical weathering.—The processes of chemical weathering—decomposition—are commonly stated to be solution, hydration, carbonation, and oxidation. "Hydration" is used in a general sense by geologists to cover the weathering effects of the union of water and

rock minerals. This is said to be the most important process of decomposition.

The addition of water to anhydrite to form gypsum according to the equation (1) is simple hydration:

$$(1) \qquad CaSO_4 + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O \,.$$

The reaction, between feldspar and water, however, involves the decomposition of both and is not hydration in the sense of equation (1). This reaction is hydrolysis, and by soil workers it is considered the most important of the processes of decomposition.[49]

A recent paper[50] dealing with the decomposition of minerals by water summarizes the older work and presents new data in an admirable manner. By grinding silicate minerals in water and measuring the hydrogen-ion concentration resulting from the hydrolysis of the minerals, Stevens obtained results which he believes are a rough index to their weathering qualities. A number of the rock-forming minerals in Table 18 were investigated, and there is a noteworthy correlation between the results obtained by Stevens and the suggested mineral-stability series.

The role of carbon dioxide.—That carbon dioxide or carbonic acid enters into weathering processes in some significant capacity is doubted by few, and experimental data show the greater effectiveness in the attack of silicates by water containing carbon dioxide than by pure water. The question immediately arises as to how the presence of carbon dioxide would affect the process of hydrolysis, and here, indeed, the results of Stevens' work appear to be highly pertinent.

The hydrolysis of orthoclase (for example) may be represented by the equation

$$(2) \qquad 2KAlSi_3O_8 + 2HOH \rightarrow 2KOH + 2HAlSi_3O_8 \,.$$

If an aluminosilicic acid is formed according to equation (2), it would be highly unstable and decompose, yielding colloidal silica

[49] G. W. Robinson, *Soils: Their Origin, Constitution, and Classification* (London: Thomas Murby & Co., 1936), p. 44.

[50] R. E. Stevens, "Studies on the Alkalinity of Some Silicate Minerals," *U.S. Geol. Surv. Prof. Paper 185-A* (1934).

and a colloidal complex. The latter under certain conditions crystallizes, forming kaolinite, while the colloidal silica is removed by solution.

Stevens ground orthoclase in an agate mortar with one drop of phthalate buffer solution at pH = 5.0 and found that after three minutes of grinding the acidity of the buffer had been neutralized. The solution became alkaline, pH = 8.8, and, at this hydrogen-ion concentration, equilibrium was established. Grinding orthoclase with an alkaline buffer solution, pH = 10.0 resulted in no change in pH — the orthoclase was not attacked.

Returning to equation (2), supposing carbon dioxide should be bubbled though the solution, potassium hydroxide and carbonic acid would react to form carbonate and water. The result is that hydroxyl-ions are removed, and the alkalinity is thereby appreciably reduced. Reaction (2) continues until the carbonic acid is neutralized and until equilibrium is again established. The role of carbon dioxide may be chiefly in the control of alkalinity rather than in the direct attack of the carbonic acid. Other possible effects of the carbon dioxide on the solubilities of the salts and on the nature of the clay mineral produced are not considered here.

Further chemical study of the changes produced by weathering is needed, but it is particularly desirable that such work be correlated with the quantitative study of the actual mineral changes. This line of investigation has been neglected largely because of the difficulties encountered in the quantitative estimation of minerals in weathered materials and residual clays. New methods and techniques are needed to facilitate quantitative mineralogical study. Quantitative mineralogical data should lead to a better understanding of the relative stability of minerals and of the physical and chemical conditions which influence their susceptibility to alteration.

THE EFFECT OF PRESSURE ON THE RIGIDITY OF ROCKS. I

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ABSTRACT

A dynamical method has been adapted to the measurement of the velocity of torsional waves in cylinders of rock exposed to pressures as high as 4,000 kg/cm², at 30° C. and at 100° C. From these results the rigidities of the rocks under these conditions are derived, as well as approximate values for the pressure and temperature coefficients of velocity and rigidity. Very large changes of rigidity are observed in many cases upon the application of the first few hundred atmospheres; at high pressure the change of rigidity with pressure becomes nearly linear and small. The following questions are discussed: stress conditions in aggregates of crystals, the effect of anisotropy upon velocity, the calculation of other elastic parameters from rigidity and compressibility, damping and dispersion in rocks, the effect of combined pressure and temperature on velocity in the earth's crust, and the identification of materials in the crust by comparison with seismological data.

INTRODUCTION

The identification of the materials of the inaccessible depths of the earth's crust has hitherto depended upon a correlation, guided by geological theory, of the velocities found for seismic disturbances with values of compressibility of rocks determined in the laboratory, and chiefly at the Geophysical Laboratory of Washington. While the compressibility is of interest in itself in affording estimates of the change of density of definite rock types when subjected to the pressures computed for various depths in the earth, still the chief use of compressibility has been in effecting comparisons with the seismic-wave velocities. The importance of compressibility data has been due partly to the fact that it has not been possible until recently to measure any other elastic coefficient of rocks under high pressure. For the purpose of finding the velocities in given rock samples under the conditions existing in the upper part of the crust, the compressibility data are incomplete in three respects. First, the velocities are not determined by the compressibility alone; it is necessary to know one other elastic parameter. This difficulty has been met by assum-

[1] Paper No. 38, published under the auspices of the Committee on Geophysical Research and the Division of Geological Sciences at Harvard University.