Mineralogical and Chemical Studies of Soil Formation From Acid and Basic Igneous Rocks in Missouri

R. P. HUMBERT and C. E. MARSHALL

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FOREWORD

The earlier history of soil science represents studies and mental processes that were mainly analytical. The various sciences viewed the soil as a natural body in which each might exercise its particular procedures as help in taking apart the soil properties and behaviors. Geology, mineralogy, crystallography, petrography, chemistry, physics, bacteriology, plant physiology and others made their contributions to the limits of refinement in their methods. Only recently have more delicate techniques come to the examination of soils in the form of the ultramicroscope, the spectrograph and the electron microscope.

These aids to our greater comprehension have made it possible for more recent soil science to become studies and mental processes mainly synthetic. Students of soils are now piecing together these contributions of the different sciences to our own knowledge about soils, into a distinct soil science. This newer science of soils presents a picture of the processes whereby rock becomes soil or solubles and contemporaneously contributes the elements serving to nourish plants for animal and human sustenance.

Plant production on any one soil is not wholly a matter of any single soil factor that any one science can elucidate. It is a carefully synthesized concept, for the completion of which all possible soil information by all sciences is needed. Colloidal chemical techniques applied to the clay fraction of the soil have interpreted the functions of this soil separate in provisioning plants for only a limited time. Interactions between the exhausted clay and the mineral silt separates as a means of restocking the clay with plant nutrients were then discovered and emphasized. The entire mineral array within our soils, as well as the colloidal array is thus brought into prominence as fundamental to plant production and agriculture itself.

For these reasons intensive mineralogical and chemical studies of rock changes in the course of soil formation and soil development have been undertaken. Missouri's varied geology offers excellent opportunity, not only to explain the productive properties of her many soils by these variations, but to develop some principles basic to understanding the productivity of soils, in general, in terms of their parent material and the forces forming soils from them. This publication is the first of a series of studies of the different rocks in their changes to form soil, of the manner in which these changes determine the chemical possibilities of the soil for agricultural production.

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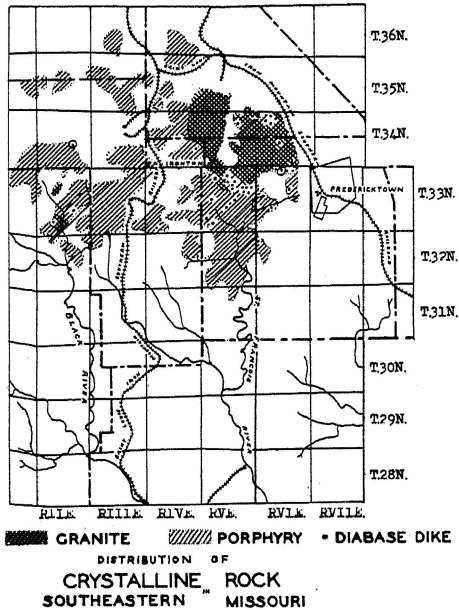*Chairman, Department of Soils*

ACKNOWLEDGEMENTS

Fig. 1.—Crystalline rocks in Missouri, after Haworth (9).

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R. P. HUMBERT and C. E. MARSHALL

The study of soil formation and development in the central United States has added much to our knowledge of soils over the world. The detailed methods of soil survey which have been practiced for many years have given us a sound basis of field observation. When this has been combined with laboratory studies and with the readily available climatic data, valuable generalizations have emerged. In one respect, however, workers in the Mississippi basin have been at a disadvantage. For the most part the soils of this region have been formed from rocks which are themselves secondary in origin: from sandstones, shales, limestones and glacial and fluviatile deposits. The variation in the chemical nature of the parent material over a given climatic zone is apt to be small and erratic under such circumstances. On the other hand a well ordered sequence of igneous rocks presents a much greater range of chemical or mineralogical composition. Hence in observing soil formation from such materials the scientist is able to disentangle with greater certainty the factor parent material from the skein of other factors which have played their part.

It is fortunate, therefore, that in Southeastern Missouri there outcrops over a considerable area, a group of igneous rocks. They occupy about seventy square miles, largely in St. Francois, Iron and Madison Counties (Figure 1). This area of crystalline rocks known as the St. Francois mountains forms the eastern part of the Ozark uplift. The summits stand 500 to 800 feet above the valleys and from 1200 to 1000 feet above sea level. Agriculturally the region is poor, the slopes being in timber and only the valley lands in cultivation.

These igneous rocks consist of a typical granite and a more perfectly crystalline porphyry of approximately the same chemical composition. There are present also, but in much smaller amount, intrusions of a basic igneous rock, a diabase. They take the form of narrow veins unsuited to soil investigations because of their limited area, and here and there of larger bosses on which good samples can be taken. These rocks are supposedly of pre-Cambrian age, they were at one time buried under paleozoic sediments which were subsequently removed by erosion. At present they are bordered by stratified sandstones and limestones which show themselves in the valleys (9).

The area in which the igneous rocks lie has never been glaciated. It is probable, therefore, that weathering and soil formation have proceeded under a variety of climatic conditions for a great length of time. The present day climate is characterized by an annual rainfall of 42-48 inches spread over all months of the year but heaviest in spring and early summer. The mean annual temperature is 54-56° F. Periods of extreme cold are of short duration in winter whilst summer temperatures of 90° and over are common. The growing season averages 180 days.

This study is essentially a comparison of the processes of rock breakdown and soil formation as they have occurred on the granite porphyry, the acid igneous rock, and the diabase, the basic igneous rock. The mineralogical changes have been followed by microscopic examination of thin sections of the rocks in various stages of decomposition and of fractions obtained in the mechanical analysis of the residual soils. Those secondary products which have remained in the soil profile have been carefully characterized. In this work the electron microscope has played an important part. Finally, various chemical determinations have been carried out on different horizons of the soil profile as part of the background of information needed in comparing these soils with those of other regions.

OUTLINE OF METHODS

Thin sections were made of the two parent materials showing varying degrees of weathering. An examination of sections of the unweathered rocks provided quantitative estimates of the original mineral constituents. The minerals observed in these sections show the sequence of changes and the relative rates of weathering of the different minerals.

Detailed mechanical analyses were made to obtain the size distribution of the particles in the various horizons of the residual soils. In order to facilitate the mineralogical analyses of the sands and the coarse silt, heavy liquid specific gravity separations were made. The large percentage of heavy minerals (Sp. Gr. $>$ 2.80) in the basic igneous profile made a magnetic separation useful. Quantitative counts of the mineral suites (minerals present in a sample) were obtained to give an accurate index of the stability of the minerals.

The characterization of the finer fractions involved the use of special techniques. It was essential to determine various optical properties in order to establish the identity of the clay minerals present. Indices of refraction were obtained through the use of dark field methods of illumination. Specific gravity determinations were made with the clay in its natural, hydrated state by the use of a sedimentation series with varying proportions of potassium mercuric iodide and water. Measurements of the double refraction of the clay particles were made in a specially designed apparatus that orients the particles in an electric field.

These data, when correlated with the structures of the clay minerals, as revealed by a series of electron micrographs, give a clearer picture of the products of weathering. The electron microscope has proved invaluable in identifying and following transitions of secondary products as they appear in the weathering of rock to soil.

The mineralogical studies were supplemented with various chemical analyses of the horizons of the profile. The analyses include determinations of (a) the total exchange capacity, (b) the total exchangeable bases, (c) the exchangeable calcium, magnesium, potassium and sodium, (d) the pH, and (e) the total carbon. Official methods of analysis of the Association of Official Agricultural Chemists were used. pH measurements were determined with a Beckman glass electrode pH electrometer. Carbon determinations were obtained by ignition in a combustion furnace. All chemical analyses were carried out in duplicate.

The experimental procedures used in this study are a combination of the techniques described in Milner's "Sedimentary Petrography" (23), Krumbein and Pettijohn's "Manual of Sedimentary Petrography"(15), and Marshall's "Mineralogical Methods for the Study of Silts and Clays" (19). The details where necessary are given along with the results in the appropriate sections.

SOIL PROFILE DESCRIPTIONS AND VOLUME WEIGHT DATA

Residual Granite Soil

The Ashe stony loam. All of the various stages of disintegration are well shown, from the solid unweathered mass, to the residual soil. The joints, caused by contraction of the igneous masses on cooling, afford surfaces for initial weathering. The seams become wider as disintegration and decomposition proceed until at present the resultant rounded granite boulders are seen widely distributed. These boulders are host to the persistent vegetative pioneers, the lichens, the algae, and the mosses.

Under normal erosion conditions a residual mantle of soil develops. The profile selected for this study was weathered from a typical granite porphyry located four miles west of Fredericktown, Madison County, on the Fredericktown-Ironton Highway. The granite porphyry is a holocrystalline, porphyritic rock containing predominant phenocrysts of orthoclase and quartz in a medium to fine grained ground mass of light to dark gray color.

The description of the residual soil profile is as follows:

0 An extremely shallow organic layer, dark brownish gray in color, consisting of well decomposed leaf litter of the post oak vegetation.

1 0-4", A grayish brown silt loam with a granular structure. The color reflects a lower organic matter content than that mapped in the Ashe series confined to the Blue Ridge and Great Smoky Mountain ranges. pH 5.4 (A_1) Vol. Wt. = 1.42

2 4-10″, A brownish yellow, friable silt loam with a granular structure.
   pH 4.6 (A₂) Vol. Wt. = 1.34

3 10-18″, A yellowish brown silty clay loam with a well developed blocky
   structure. The blocks range in size from ¼″ to 1½″ in diameter.
   pH 4.4 (B₂) Vol. Wt. = 1.28

4 18-24″, A brown, sandy clay loam with a poorly developed blocky struc-
   ture. The soil is friable and contains numerous weathered rock
   fragments. pH 4.3 (B₃) Vol. Wt. = 1.31

5 24-30″, A light brown, gritty sandy loam with a somewhat granular
   structure. pH 4.4 (C) Vol. Wt. = 1.53

Bedrock: 30″, A soft, disintegrated granite porphyry, light pinkish gray
   in color mottled with yellow and brown. pH 5.3

Residual Diabase Soil

The diabase occurs in dikes scattered irregularly throughout the
entire crystalline area. The dikes are commonly small seams cutting
the granite and average only 2 to 3 feet in width. Their color is
generally a dark green or black, with occasional white streaks of
feldspar. The soil profile selected for this study was weathered
from the typical diabase of the Black River boss. This is the
largest basic intrusion known in Missouri and is located 24 miles
west of Skrainka, Iron County (Tp. 34 N., R. II E., Sec. 26). It
occupies an area of about 160 acres, with a large portion now under
cultivation. The pioneers apparently recognized the fertility of
the soil through the luxuriant vegetation, as compared with the
scrub growth on the infertile soils of the granite areas. The soil
of the cultivated fields from a distance shows a greenish cast as a
result of the large proportion of epidote and hornblende. Number-
less smaller dikes occur in the vicinity of the large boss, all com-
posed of the same material. The similarity of the diabase, even as
far east as the quarry at Skrainka, suggest that the dikes are con-
temporaneous, and that they had a common origin. Variations that
do exist can be attributed to a variation of physical conditions
under which the molten material solidified.

Fig. 2.—Exfoliation of diabase boulder.

The decomposition of the diabase is rapid. Where erosion is accelerated, boulders are exposed showing typical exfoliation. Fig. 2 exhibits one of these boulders and its "onion skin weathering."

The description of the residual soil profile is as follows:

0   A shallow organic layer, dark brownish gray in color, consisting of well decomposed forest debris with a thickness averaging less than ½ inch.

1   0-5", A brownish gray silt loam with a soft granular structure in the lower part. This horizon contains a relatively high content of organic matter. pH 5.1 (A_1)   Vol. Wt. $= 1.04$

2   5-9", A yellowish brown to brown silt loan layer having a poorly developed platy structure. The transition to the blocky structure of the B horizon is not sharply defined. pH 4.8 (A_2)   Vol. Wt. $= 1.07$

3   9-16", A medium brown silty clay loam with a moderately well developed blocky structure. The aggregates range in size from ¼" to 1" in diameter. pH 4.9 (B_2)   Vol. Wt. $= 1.11$

4   16-21", As 3.   pH 5.1   Vol. Wt. $= 1.33$

Fig. 3.—Residual diabase soil profile.

5   21-25", A light brown silty clay loam grading from a moderate to a poorly developed blocky structure. This transitional zone to C includes an increasing percentage of rock fragments with depth. pH 5.2 (B_3)   Vol. Wt. $= 1.27$

6   25-33", A yellowish brown silty clay loam with a massive structure. pH 5.5.   Vol. Wt. $= 1.22$

7   33-47", The dominance of yellow persists to 47".   pH 5.6.   Vol. Wt. $= 0.96$

8   47-60", Veins of dark grayish brown clay extend to 60", suggesting mechanical transportation in root channels. The large masses contain a relatively high proportion of rock fragments but nevertheless break down readily into smaller units. pH 6.0 (C)   Vol. Wt. $= 1.11$

Bedrock 60", A soft, disintegrated and partially decomposed diabase of greenish brown color, speckled with gray, yellow, brown and black.

THIN SECTION STUDIES

Thin sections were made of the unweathered rocks and of both the granite and diabase in various stages of decomposition. Approximate percentages of the original constituents were obtained by detailed analysis of the sections made from the unweathered rock. The changes in mineralogical composition which occur in the transformation from rock to soil were followed through an examination of the above mentioned series of thin sections.

Granite

The mineralogical composition of the granite includes the following minerals in order of their relative abundance: orthoclase, quartz, iron oxides, biotite, hornblende, microcline, albite, apatite, zircon, fluorite, rutile, titanite, garnet, and pyrite.

Feldspars: (53%)—The feldspars include orthoclase, microcline, and a smaller amount of sodic plagioclase. They are present both as phenocrysts and in the ground mass of the porphyries. Since orthoclase is one of the latest minerals to crystallize, it shows no crystal boundaries except against quartz, which separated later. Magnetite frequently altered to hematite dominates the inclusions. While primary inclusions are not especially common, secondary products are abundant, giving the mineral its clouded appearance. It is commonly supposed that on hydration and liberation of exchangeable cations, the reaction with CO_2 produces precipitation which aids in giving the mineral its clouded appearance. This widespread alteration indicates the ease with which this mineral is decomposed. Analyses of the series of slides show the mineral to retain its crystal form long after its optical properties have begun to change. The clay minerals formed were found in many instances along planes of weakness. (Fig. 4). The red and yellow colors of the secondary products of weathering are due to stains of iron oxide.
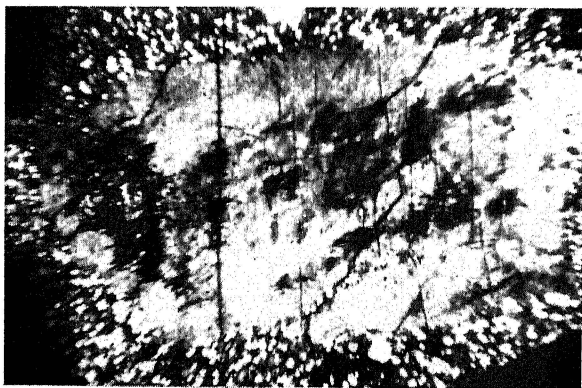

Fig. 4.—Photomicrograph of weathering feldspar phenocryst.

Granite selected from a quarry near Ironton, Missouri, presents both potassium feldspars; microcline and orthoclase. The microcline shows the characteristic polysynthetic or gridiron twinning and its stronger resistance to the agents of weathering.

The plagioclase feldspars occur much more sparingly than either of the potash feldspars and are scarce in the granite underlying the soil profile studied. The optical properties of the minerals indicate the presence of the most sodic member, albite.

Quartz: (32%)—The study of the quartz crystals in the thin sections reveals the possibility that the quartz phenocrysts began to crystallize before the feldspar had completely solidified. The quartz in the phenocrysts occurs in rounded or embayed crystals. In the latter form, the material of the ground mass extends into the embayments (Fig. 5), indicating the early formation and subsequent magmatic corrosion of the crystals.

Quartz comprises approximately 32% of the rock and occurs both as phenocrysts and as small irregular crystals in the ground mass. The appearance of the quartz in the ground mass of the unaltered rock proves the quartz was the last mineral to crystallize since it occupies the interstices between the other constituents. Occasionally the grains show undulatory extinction. This is due to the gradual change in the orientation of the crystal axis in different parts of the crystal produced from stresses and strains. The crystals are commonly cracked as a result of these stresses
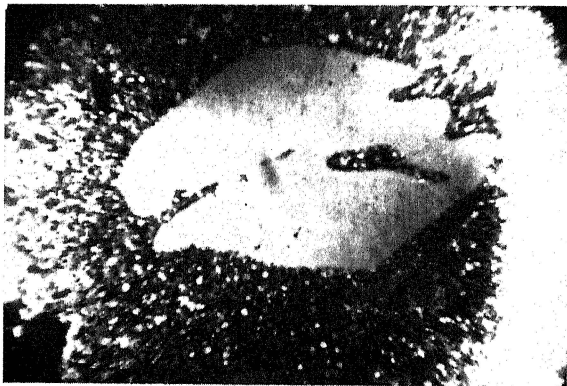

Fig. 5.—Photomicrograph of embayed quartz crystal.

Fig. 6.—Photomicrograph of fracture of quartz phenocryst.

and strains and this characteristic offers some of the most logical explanations of the breakdown of the large phenocrysts in the formation of soil. (Fig. 6).

Quartz is generally regarded as one of the most stable minerals. However, the fact that the size of the quartz phenocrysts exceeds the maximum sized grains in the residual soil necessitates an explanation. The largest quartz crystal in the sand fractions measured only 1.9 mm. while quartz phenocrysts in the unweathered rock measured up to 3 mm. in diameter. The stability relations of quartz are dependent primarily upon the conditions of cooling· of the magma. The $a—\beta$ inversion of quartz has been the subject of considerable investigation since the phenomenon was first observed by LeChatelier in 1890. Fenner (5) determined the temperature of inversion in a thermal microscope as $575° \pm 2°$ (inversion point on heating), and $570° \pm 2°$ for the inversion point on cooling.

Experiments have shown that in cooling from 600° to 550° the volume of quartz decreases about 2%. This contraction is sufficient to account for the fracture. It is very probable that the effect of the agents of weathering since pre-Cambrian time is adequate to complete the breakdown of the larger, cracked crystals. This explanation does not contradict the belief in the chemical stability of quartz crystals, but merely explains their physical breakdown. Recent work distinguishing between a and β forms gives to quartz considerable value as a geologic thermometer.

The milky color shown in many grains is due to the reflection of light from innumerable liquid and gas inclusions. At high magnification (800X) the inclusions display brownian movement. Several investigators have offered nitrogen, liquid CO_2, and liquid carbonic acid as the possible constituents. Inclusions are very common and since the quartz is the last mineral to crystallize, it may contain any of the other constituents. The minor accessory minerals—magnetite, apatite, and zircon—are seldom absent. Observations from the sections from highly weathered parent material show alteration products oriented along the cracks in the phenocrysts.

Micas (3%) Biotite.—The biotite occurs very sparingly in brown, flat, hexagonal plates and poorly defined flakes. Apatite, zircon, and magnetite occur as the principal inclusions in the mineral and served as possible starting points for its crystallization. The first indication of alteration is the production of a golden luster on hydration. Under the microscope this alteration appears as a bleaching effect. The next step in alteration is the development of a green color. This is the beginning of chloritization, for the mineral still retains the high double refraction of biotite. Following this is the destruction of the crystal pattern resulting in the formation of chlorite, epidote, and other similar products.

Further alteration of the chlorite and epidote may give quartz, calcite, clay minerals, and iron oxides.

Muscovite.—Primary muscovite was entirely absent from the granite from which this study was made. Secondary mica was produced in the form of sericite from the decomposition of the feldspars.

Iron Oxides (8%).—The prevalence of the oxides of iron necessitate their detailed description. In the slides obtained from the fresh rock, the iron occurs as magnetite in distinct crystal form and also as clusters or aggregates of smaller granules. Through the series of thin sections the magnetite, especially that in aggregate form, is more and more oxidized to hematite. In the most highly weathered section, multitudes of exceedingly small grains arranged in a definite pattern indicate the presence of a former mafic mineral, possibly biotite or hornblende. As a secondary mineral,

magnetite is derived from the ferromagnesian constituents and is usually accompanied by chlorite. Hematite is present as a primary mineral as small inclusions in the quartz. As a secondary mineral it occurs in irregular forms of reddish to opaque crystals. It is very prominent as red films in cracks between the other constituents. Its presence in the altering feldspar phenocrysts gives the clay minerals produced a reddish to yellowish iron oxide coating.

Ilmenite occurs in its characteristic skeleton form more or less altered to leucoxene.

Hematite, often containing titanium, occurs in the form of specular iron as inclusions in the other constituents, and in this form is a primary mineral and among the first to crystallize.

Limonite, $2 Fe_2O_3$. $3 H_2O$, does not occur in crystalline form but in amorphous masses or films. Its color varies from yellow to dark brown. It is derived from magnetite, pyrite, or the ferromagnesian minerals, and is always secondary.

Hornblende (2%).—Hornblende occurs in very minute quantities in brownish green crystals of very irregular form. Its association with clusters of fine granules of magnetite indicate hornblende may have occurred in larger proportion.

Accessory Minerals (3%).—In the thin section studies, only a few of the most prominent species of accessory minerals present are detected. This is partly due to their comparative scarcity with reference to the principal constituents, and partly due to their small size. However, the studies did reveal a rich and varied collection of species.

Apatite $Ca_4(CaF)(PO_4)_3$.—This phosphate bearing constituent occurs in long, colorless microscopic needles and as minute six-sided prismatic crystals. Its persistence in the series of sections classifies it as moderately resistant.

Fluorite CaF_2.—Fluorite occurs as small, isotropic crystals showing chonchoidal fracture. It is fairly resistant to weathering, but does alter to calcite by the action of percolating waters containing calcium bicarbonate or alkaline carbonates.

Garnet.—Group of orthosilicates. Garnet is present sparingly and shows strong resistance to weathering. Some species of garnet are more easily weathered and their products of decomposition include chlorite.

Pyrite FeS_2.—Pyrite occurs in opaque euhredral to irregular brass colored grains showing a metallic luster in reflected light. Alteration to hematite and limonite are common.

Rutile TiO_2.—Rutile is present as yellow needles as a common inclusion in the quartz. Its high relief and extreme birefringence are characteristic. It alters to leucoxene as does titanite.

Zircon $ZrO_2.SiO_2$.—Zircon occurs as inclusions in the quartz and ferromagnesian minerals. The largest crystal observed measures only 0.10 mm. while the majority are much smaller. The crystals exhibit pleochroic zones and are extremely resistant to weathering.

Titanite.—$CaO.TiO_2.SiO_2$ with small amounts of MnO, MgO, Al_2O_3, and Fe_2O_3. It occurs in colorless to yellow crystals showing partial alteration to leucoxene.

Secondary Minerals

Chlorite (Essentially silicates of aluminum, ferrous iron, magnesium and hydroxyl).—The chlorites occur in various shades of green colored scales, fibers, or ill-defined particles. These mica-like minerals are never primary but are produced by the alteration of pre-existing aluminous, ferromagnesian minerals such as biotite, hornblende, augite, epidote, garnet, etc. Their stability is limited and the transition to the clay minerals is fairly rapid.

The chlorites are characterized by their green color, flaky appearance, and good cleavage.

Epidote (4 $CaO.3(Al,Fe)_2O_3.6SiO_2.H_2O$).—Epidote occurs as one of the products of decomposition of the ferromagnesian minerals, with the calcium supplied from the weathering of the plagioclase feldspars. In color, epidote ranges from green to yellow to brown. The noticeable range in optical properties is due to the variation in the percentage of iron. The stability of epidote is much greater than that of associated chloritic products; however, this secondary product must not be classified as an entirely resistant mineral.

Sericite ($K_2O.Al_2O_3$. 6 SiO_2. 2 H_2O).—This secondary muscovite-like mineral is derived essentially from the feldspars. It differs from the muscovite in habit by forming aggregates of elongated shreds, and in its secondary nature. The chemical changes which occur in its transformation were given in the discussion of the feldspars.

Clay Minerals.—The clay minerals occur in flakes, fan-shaped aggregates, and earthy masses of finely disseminated flour-like dust. The more crystalline forms are easily mistaken for sericite. The differences between the two lie chiefly in the higher extinction angle, lower indices of refraction, and lower birefringence of the clay minerals.

The successive appearance of the above weathering products in the series of thin sections was very striking. The ferromagnesian minerals were the first to alter beyond recognition. The alteration of the feldspars followed but they were still recognizable in the most highly weathered sections. The quartz and many of the accessory minerals proved their resistance to the agents of weathering in remaining practically unchanged. Indications of the penetration of the oxides of iron into the larger quartz crystals, however, were noticed in the more weathered sections. These changes will be followed closely in the examination of the residual soil.

Diabase

The mineralogical composition of the diabase includes the following minerals in order of their relative abundance: Plagioclase, augite, olivine, iron oxides, hornblende, biotite, quartz, apatite, chlorite, epidote, magnesite, garnet, and pyrite.

Fig. 7.—Photomicrograph of ophitic texture of diabase.

Plagioclase (40%).—The plagioclase feldspar, laboradorite, occurs in long, slender lath-shaped twinned crystals, and comprises approximately 40% of the rock. The size of crystals range from one centimeter to microscopic dimensions. The ophitic texture of the diabase has generally been accepted as due to the crystallization of the plagioclase feldspars before the crystallization of the augite. (Fig. 7).

The plagioclase alters to a mixture of various minerals giving rise to an earthy appearing substance, nearly white in color, harder than labradorite, of greater specific gravity, and megascopically without luster or cleavage. This mixture, called saussurite, is composed essentially of plagioclase, albite, and epidote, with accessory fibrous hornblende and chlorite. The iron necessary for the formation of epidote is derived from the ferromagnesian minerals. Calcite occurs rarely, indicating that the calcium liberated through hydrolysis is tied up immediately in the silicate, epidote. Flakes of secondary chlorite and amphibole, derived in part from the ferromagnesian minerals and in part from the laboradorite, often occur and give to the saussurite aggregate a green tint.

It is a common observation that the borders of the feldspar crystals are in a better state of preservation than their centers. This phenomenon may be explained by the intimate relationship of the greater molecular stability of the sodic periphery in comparison with that of the more calcic center. Harker (10) suggests variations in chemical composition with zoned plagioclase crystals and Tomkeieff (28) reports a continuous zoning from calcic center to sodic periphery.

Augite (30%).—The pyroxene augite occurs as dark gray to black irregular grains filling the spaces between the feldspar laths, and comprises about 30% of the rock. The grains are short and tabular, and appear a pinkish buff in transmitted light, due to the presence of titanium.

In the weathering of this mineral the alteration begins at the margins and along the cleavage and fracture lines. The common alteration produced is green hornblende. It is recognized as secondary by the irregularity of the inner portion of the hornblende border. This common alteration process is called uralitization. Uralitization is not a simple change of pyroxene to amphibole, but is a complicated process accompanied by other chemical changes so that the amphibole is associated with secondary magnetite, epidote, chlorite, and calcite.

Further alteration produces the secondary mica, with optical properties similar to biotite, found in abundance in the lower horizons of the soil profile. According to Bragg (2), there is a close relationship between the mica structure and those of the pyroxenes and amphiboles. In fact, the mica structure can be considered as produced by an extension of the process which converts a pyroxene into an amphibole. The single chains of a pyroxene are joined together to form a double chain in the amphibole, and if further chains are added the hexagonal network of mica is produced.

Olivine (10%).—Olivine comprises approximately 10% of the original rock and occurs in somewhat spherical irregular grains. Cleavage lines are seldom present but fracture lines are very abundant. The grains are clouded only by small magnetite inclusions and the majority of grains exhibit their usual characteristic watery, transparent, very light green color with transmitted light.

Alteration begins at the surface presented by the borders and the fracture lines of the crystals producing a pleochroic green product which appears to be fibrous hornblende or actinolite. Figure 8 shows the production of delicate fibers at a fracture line of an olivine crystal. The fibers are seen to develop at right angles to the surface exposed. This often leaves rounded, unaltered fragments of the original mineral between the cracks,
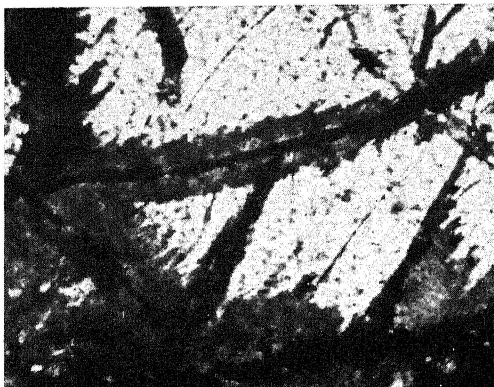
Fig. 8.—Photomicrograph of weathering crystal of olivine.

which are sharply marked by minute crystals of magnetite. The rate of decomposition of olivine is exceptionally rapid.

Quartz (1%).—The occurrence of quartz is rather unusual in rocks as basic as this diabase. Quartz crystals exist in small quantities in the dike rocks of the same vicinity from which the soil profile was taken. Primary quartz occurs only rarely and comprises less than 1% of the rock. Examination of the residual soil shows an accumulation of both quartz and chalcedony. The origin of some of the secondary silica minerals was ascribed to the plagioclase feldspars.

Other Accessory Minerals

Iron Oxides.—The iron oxides occur as abundant constituents and comprise approximately 16% of the rock. Magnetite, titaniferous magnetite, and ilmenite are all present with the former occurring in larger proportions. The latter two often show alteration to white, amorphous leucoxene. The increasing percentage of the oxides of iron in the thin sections of the more highly weathered material classifies these minerals as resistant. The forms present indicate the predominance of the crystals of secondary origin.

Apatite.—Apatite is everywhere present in the dike rocks, in the form of long, slender crystals penetrating the other larger constituents and in shorter prismatic grains. The persistance of the hexagonal outline of the crystals in the weathering series classifies apatite as fairly resistant.

Garnet.—Garnet occurs sparingly in brown or black colored crystals. They are probably lime-iron garnets, and should be referred to the variety melanite.

Secondary Minerals

Chlorite.—Chlorite occurs as a secondary product with no regularity of form. It constitutes small patches scattered through the weathered olivine, augite, and hornblende crystals. Occasionally it occupies the entire space left by the decomposition of crystals of the minerals mentioned.

Epidote.—Epidote occurs in irregular, rounded grains of secondary origin from the alteration of the plagioclase feldspar. The supply of the iron necessary for their formation was discussed under alteration of the feldspars.

Calcite.—This secondary mineral was found in small flakes in the badly weathered sections but never as an important constituent.

Magnesite.—The presence of small quantities of secondary magnesite indicates the abundance of magnesium released in the relatively rapid decomposition of the ferromagnesian minerals.

Comparison of Early Stages of Weathering

The mineralogical differences between the granite porphyry and the diabase are very great, as the foregoing descriptions have shown. The chemistry of the early stages of weathering, up to the point where the rocks become incoherent, whilst dominated by the general processes of hydration and oxidation, should therefore show considerable differences in detail. This is borne out by the observations.

The orthoclase feldspar of the porphyry is only partially decomposed giving rise to sericite and to clay-like products, whereas the plagioclose feldspar of the diabase produces, by reaction with ferromagnesian minerals, the mixture known as saussurite. The porphyry contains most of its iron in the form of magnetite which undergoes simple oxidation to hematite. Relatively small amounts of ferrous iron and magnesium are involved in transformations of biotite and hornblende to chlorites. Similarly, small amounts of calcium from the plagioclose feldspar present become associated with the decomposing ferromagnesian minerals to give crystalline epidote. On the other hand, the diabase contains large amounts of plagioclase feldspars and of ferromagnesian minerals. Epidote is therefore much more conspicuous in the weathered diabase than in the weathered granite porphyry. Hornblende appears as a primary mineral in the porphyry, but is secondary in the diabase in which it undergoes further alteration to mica. Thus the decomposition of the diabase involves even in the early stages practically all the constituents of the rock, whereas in the granite porphyry the minor constituents react first, followed by the orthoclase. The final breakdown of the quartz is physical, not chemical.

Mechanical Analyses

A detailed mechanical analysis was made on quadruplicate 20-gram samples of the respective horizons of the soil profiles. The international pipette method of analysis was used with modifications.

Experimental Procedure.—Pre-treatment: 20.000 ± .005 gms. of air dry soil were placed in 600 cc. beakers. The sample was treated twice with 50 cc. of 6% H_2O_2 and digested on a steam bath to remove the organic matter. Ten cc. of 1 : 20 HCl were added to make the suspensions approximately .1 N in hydrogen ions. After standing over night, the suspensions were washed into Buchner funnels with distilled water and leached five times with 1 : 100 HCl and then ten times with distilled water to remove the excess acid. The samples were then transferred quantitatively to shaker bottles. They were then titrated to a pH 8.5-9.0 with NaOH, using phenolphthalein as indicator, and shaken in a mechanical shaker for a period of 24 hours. Distilled water was then added to a weight of 1000 gms. and the shaker bottles placed in a constant temperature bath at 30.0° ± .1° C.

Mechanical Analysis.—The shaker bottles were shaken one minute before each sampling. Twenty-five cc. samples were pipetted at 10.2 cm. depth at proper time intervals for $<20\mu$, $<10\mu$, $<5\mu$, and $<2\mu$ fractions. The

sands were removed on a 300 mesh sieve and the fractions were weighed after sieve separations.

Fractionation.—The $<2\mu$ fraction was removed with the shaker bottles in the temperature controlled bath. The 2-5μ and 5-20μ fractions were removed by siphoning at a depth of 10.2 cm. at room temperature. The time was corrected for the temperature of the water during fractionation. The siphoning process was repeated seven times to insure practically complete removal of a given size fraction.

Results of Mechanical Analysis

Residual Granite Soil.—A decrease of particles greater than 20μ in the profile from the surface to a depth of 18 inches is evident in Table 1. Below this depth a gradual increase of particles of this size is obtained. The particles 20 - 5μ in size decrease in proportion from the surface soil to the parent material with the silt fraction remaining practically constant in the upper horizons and dropping off in the crushed rock fragments. A definite accumulation of the clay fraction ($<2\mu$) occurs at a depth of 10 - 24 inches. The distribution of the clay in the profile indicates that the clay, weathered from the feldspar in the surface soil, moved to the B horizon, as indicated by an increase from 14.5% in the surface soil to 39.9% at a depth of 10-18 inches. Further fractionation of the clay separate reveals the movement of the finer clay particles. The

TABLE 1. MECHANICAL ANALYSES OF RESIDUAL GRANITE SOIL (OVEN DRY BASIS)

Sample Number	Depth in in.	>50mm %	.50-.25mm %	.25-.05mm %	.05-.02mm %	.02-.01mm %	.01-.005mm %	.005-.002mm %	<.002mm %
1	0-4	2.47	1.22	2.12	27.49	30.05	14.35	7.50	14.5
2	4-10	1.15	.78	1.42	21.61	30.2	13.5	8.12	23.2
3	10-18	.58	.61	1.40	13.02	23.3	13.45	7.75	39.85
4	18-24	2.23	1.22	1.72	15.42	23.8	11.8	9.00	35.9
5	24-30*	11.06	3.92	2.83	26.03	17.6	9.55	5.05	24.1
6	26	8.38	3.88	3.57	22.02	19.6	10.25	5.65	27.0
7	24-30	22.91	7.10	4.79	32.11	16.6	7.60	3.21	6.29
8	26	34.50	12.01	8.42	23.94	12.2	4.30	1.51	4.18

CLAY FRACTIONATION

Sample Number	Depth in Inches	Size Distribution 2-.5 μ %	<.5 μ %	Water lost between 110° and Ignition at 1000° C 2-.5 μ %	<.5 μ %
1	0-4	46.2	53.8	7.34	13.2
2	4-10	38.2	61.8	7.62	12.4
3	10-18	24.1	75.9	7.67	12.0
4	18-24	19.4	80.6	8.73	12.0
5	24-30*	21.0	79.0	11.13	10.4
6	26	21.7	78.3	9.60	11.2
7	24-30	42.8	57.2	8.37	12.3
8	26	58.5	41.5	7.69	14.1

* 5 Decomposed hull of weathered parent material
  6 Partially decomposed hull enclosing unaltered granite
  7 Crushed fragments of weathered parent material
  8 Crushed fragments of unaltered granite

clay fraction of the surface soil consists of 46% of 2 - .5μ material while in the B horizon the material <.5μ comprises 80% of the fraction.

The comparison of the hydration of the different sized particles of the clay separate is given in Table 1. The higher losses of water on ignition of the <.5μ fraction show the smaller particles to be more highly hydrated. Water losses on ignition compare closely with those reported for beidellite.

TABLE 2. MECHANICAL ANALYSES OF RESIDUAL DIABASE SOIL (OVEN DRY BASIS)

Sample Number	Depth in In.	> .50mm %	.50-.25mm %	.25-.05mm %	.05-.02mm %	.02-.01mm %	.01-.005mm %	.005-.002mm %	<.002 mm %
1	0-5	1.30	3.97	7.59	33.97	22.36	10.48	6.73	13.37
2	5-9	0.78	2.32	4.03	26.22	19.93	12.36	8.33	26.15
3	9-16	1.59	3.82	5.87	22.63	16.27	10.77	8.18	32.00
4	16-21	4.00	6.77	9.49	21.47	12.44	9.07	7.85	29.25
5	21-25	8.47	7.71	10.85	19.13	11.63	8.09	7.46	26.69
6	25-33	4.78	7.05	11.62	19.27	10.06	7.38	7.20	33.05
7	33-47	3.93	8.13	15.01	22.19	7.53	6.12	3.67	32.74
8	47-60	9.93	16.96	22.45	21.55	6.44	3.77	3.51	15.93

CLAY FRACTIONATION

Sample Number	Depth in Inches	Size distribution		Water lost between 110° and Ignition at 1000° C	
		2-.5 μ %	<.5 μ %	2-.5 μ %	<.5 μ %
1	0-5	50.4	49.6	10.22	12.36
2	5-9	32.3	67.7	9.49	10.23
3	9-16	49.2	50.8	8.02	11.05
4	16-21	35.5	64.5	9.49	11.94
5	21-25	39.8	60.2	9.38	13.04
6	25-33	36.7	63.3	10.07	12.63
7	33-47	21.8	78.2	13.69	13.49
8	47-60	16.6	83.4	17.19	17.78

Residual Diabase Soil.—The depth of weathering under normal erosion conditions, and the total amount of clay produced, is evidence that the soil is approaching maturity. The data in Table 2 indicate two zones of intensive weathering. A reduction in coarse sand in the surface horizon and at a depth of 25-47", and a correspondingly high clay content, are noteworthy. The intensive zone of weathering in the surface soil is natural and is to be expected. The lower zone of intensive weathering may perhaps be correlated with water table activity. The distribution of particle size at the depth of 47-60" supports the belief that unweathered parent material was not far below the 60" depth. Fractionation of the clay shows a higher percentage of <.5μ clay at the lower depths of the profile.

Dehydration studies show the clay minerals in the lower horizons to be more highly hydrated than the clay of the surface soil. Ex-

planations will be given in the discussion of the nature of the clay fractions.

Heavy Mineral Studies

Quantitative studies of the various minerals in the horizons of the soil afford an interesting story of the transition from the parent material to the residual soil. In order to facilitate the analysis, further subdivisions of the soil separates were made by means of heavy liquid specific gravity separations. s-Tetra-bromethane was diluted with nitrobenzene to a specific gravity of 2.80 as recommended by Truog (29). Separations were made at a specific gravity of 2.80 to isolate the quartz and feldspars from the ferromagnesian minerals and the heavy accessory constituents. s-Tetra-bromethane gave much better dispersion than bromoform as indicated by the size of the aggregate and the speed of rise of the particles in the tube. In using s-Tetra-bromethane it is desirable to use benzene as the liquid in the protecting tubes to lessen the force on the lower end of the tubes.

Experimental Procedure.—1.0000 - .0003 grams of air dry separates were placed in the heavy mineral centrifuge tubes on top of 5.0 cc. of s-Tetra-bromethane (sp. gr. 2.80). The tubes were placed in large centrifuge tubes containing benzene standing well up on the sides of the tubes and carefully balanced. The fractions were centrifuged at 1000 R.P.M. At five minute intervals the tubes were removed from the centrifuge and shaken vigorously. After the fifth centrifuging the glass plug in the stopper was loosened to allow the pressure in the tube to reach atmospheric. The bottom cork was removed and the heavy minerals allowed to run into evaporating dishes. The flow of the liquid is stopped by pressing the glass plug tightly in place. Both the heavy and light mineral fractions were washed twice with benzene and decanted. The washings were redistilled to recover the s-Tetra-bromethane. Both fractions were washed twice with methyl alcohol and the heavy minerals placed in weighing cans and dried at 110° C. Duplicate samples were analyzed with each fraction except those indicated (*).

Residual Granite Soil.—The results of the quantitative separations of the various separates are given in Table 3.

TABLE 3. DISTRIBUTION OF THE HEAVY MINERALS IN THE SAND FRACTIONS OF THE RESIDUAL GRANITE SOIL

Sample Number	Depth (Inches)	Percentages of Fractions				Percentages of Whole Soil				
		>.5mm	.5-.25 mm	.25-.05 mm	.05-.02 mm	>.5mm	.5-.25 mm	.25-.05 mm	.05-.02 mm	Total >.02 mm
1	0-4	8.4	10.3	14.6	4.2	0.21	0.13	0.31	1.15	1.80
2	4-10	10.9	8.9	38.5	2.5	0.13	0.07	0.55	0.54	1.29
3	10-18	9.0	4.4	51.5	3.0	0.05	0.03	0.72	0.39	1.19
4	18-24	3.4	5.4	14.6	3.2	0.08	0.06	0.25	0.49	0.88
5	24-30	5.5	8.6	9.5	2.3	0.61	0.34	0.27	0.60	1.82
6	26	4.1	5.6	7.8	1.8	0.34	0.22	0.28	0.40	1.24
7	24-30	1.2	4.1	6.9	2.6	0.27	0.29	0.33	0.83	1.72
8	26	1.7	2.7	5.7	2.9	0.59	0.32	0.48	0.69	2.08

The low percentages of the heavy minerals in the Missouri granites are due primarily to the characteristically small amounts of ferromagnesian minerals.

The percentages of the heavy minerals in the residual granite soil are somewhat lower than those estimated in the thin section studies of the fresh rock. This is particularly noticeable in the parent material. The analysis of the light fraction of the crushed rock shows the feldspar to include smaller accessory crystals. It is evident that the higher specific gravity of the accessory minerals was not enough to carry the specific gravity of the aggregate above 2.80. The comparatively rapid weathering of the ferromagnesian minerals would limit the accumulation of the heavy minerals in the surface horizons. It is of interest to note the large proportion of the iron accessory minerals including concretions in the fraction .25-.05 mm.

A description of the ferromagnesian minerals, together with their products of weathering, has been given in the thin section studies. The heavy accessory minerals identified include magnetite, ilmenite, hematite, limonite, zircon epidote, fluorite, apatite, garnet, pyrite, tourmaline, rutile, and titanite.

Of the accessory minerals, magnetite is by far the most abundant, being present in greater amounts than all the other accessories and the ferromagnesian minerals combined. An abundance of the alteration product leucoxene indicates that much of it is highly titaniferous. Ilmenite was distinguished from the magnetite by its rhombohedral form, conchoidal fracture, more metallic luster, and weaker magnetic properties. Where partial alteration to leucoxene occurs, there is little fear of confusion. The oxidation of these oxides of iron to hematite and limonite is very common. Hematite occurs both as a primary and secondary constituent. As a primary constituent it varies in form from anhedral crystals to aggregates of minute grains. In many instances, as a secondary mineral, it is altered to limonite. An abundance of limonite in irregular grains and powdery aggregates shows light brown to earthy colors in reflected light. It is the most common coating of the other constituents and was removed in some instances with dilute HCl to ensure accuracy in identification.

Concretions are very prominent in the upper soil horizons and their abundance warrants special consideration. Their form is usually spherical although somewhat irregular. When broken they reveal a concentric structure indicating their origin and development. Inclusions are common. Color variations range from deep red to nearly black. Their magnetic properties seem to vary with the degree of oxidation of the iron. Those containing practically pure hematite are distinctly more magnetic. Winters (30) reports similar characteristics in color, form, structure, and magnetic properties of concretions in Illinois soils. His chemical analyses show their color varies according to their iron and manganese content; a high iron content gives a red color while a higher manganese content results in darker colors. Winters' technique of magnetization by ignition provides a convenient method for the separation of concretions from siliceous material.

Zircon ranks next to the oxides of iron in abundance. It is quite variable in color with the light tan and olive green colored grains predominating.

Their habit is euhedral with the prisms elongated in the direction of the principal axis. In size they are also quite variable, ranging up to .4 mm. in length. Both zoned and unzoned crystals are noted. The presence of inclusions is a common feature. The dusky appearance of a few of the grains is due to these inclusions and not to its alteration products. The apparent stability of zircon ranks it among the minerals most useful in correlation studies (20).

Epidote occurs in massive to fibrous aggregates and in irregular grains showing a color variation of green to yellow. Its birefringence varies from moderate to very strong, increasing with increases in iron content. Its increase in the soil horizons over its percentage in the parent material indicates its formation with the breakdown of the ferromagnesian minerals.

Fluorite occurs in the non-magnetic portions of the heavy minerals in angular, irregularly shaped colorless grains. A few grains show color spots of pink and violet.

Apatite occurs generally as fragments of barrel-shaped crystals occasionally showing terminated ends. Colorless grains predominate while pleochroic, colored varieties were noted. The crystals in the upper horizons of the soil profile show evidence of solution.

Titanite is present as yellowish brown prismatic crystals showing irregular fracture. They were characterized chiefly by their high refractive index, color, and absence of extinction.

Rutile occurs in small quantities as dark reddish-brown prismatic crystals. Frequently they were striated and nearly all grains showed weak pleochroism.

Tourmaline occurs in elongated, prismatic crystals, some being terminated by rhombohedra. The bluish-green and brown grains are most common. Inclusions were numerous, yet the mineral is remarkably free from decomposition products.

The iron and manganese garnets were identified and occur in red to brown colored, irregularly fractured crystals. Pyrite was found only sparingly in the soil profile.

The study of the heavy minerals in the coarser sand fractions made possible the tracing of the weathering of the small quantities of ferromagnesian minerals to the products, epidote and chlorite, and an analysis of the concretions formed. The concretions were found to decrease in quantity very markedly from the surface to the parent material. Oxidation of the ilmenite and magnetite to limonite and hematite in the surface horizons and the alteration of ilmenite to leuxocene were the chief notations.

Results of the quantitative counts of the medium, fine, and very fine sand fractions are given in Tables 4, 5 and 6.

The rapid weathering of the feldspars as compared to the weathering of the more resistant heavy minerals shows markedly in the increase in percentage of heavy minerals in samples 5 and 7 over samples 6 and 8. The identification of the heavy minerals in going upward through the profile shows magnetite to be oxidized to hematite and limonite at a moderate rate while the alteration of ilmenite to leucoxene and the iron oxides proceeds at a much slower rate. An absence of the ferromagnesian minerals in the upper horizons proves their limited resistance to the agents of weathering. An increase in percentage of the more resistant heavies, such as zircon and tourmaline, in the upper soil horizons gives an index as to the rates of weathering of the other heavy minerals. Examina-

tion of the heavy mineral suites in the preceeding tables shows no sharp breaks, either in percentages or in mineral species, thus indicating the weathering of the profile in place (20).

TABLE 4. HEAVY MINERALS IDENTIFIED IN THE MEDIUM SAND (.5-.25 mm.) SEPARATES OF RESIDUAL GRANITE PROFILE

Minerals	Sample Number							
	1	2	3	4	5	6	7	8
	Depth in Inches							
	0-4	4-10	10-18	18-24	24-30	26	24-30	26
Magnetite	2*	3	4	4	5	5	6	6
Ilmenite	4	4	3	3	2	2	1	2
Hematite	9	9	9	7	6	5	2	1
Limonite	3	3	4	3	1	1	1	-
Biotite	-	1	1	3	3	4	4	4
Hornblende	1	1	1	3	5	5	7	7
Zircon	1	1	1	1	-	1	1	1
Epidote	1	2	2	3	3	3	2	-
Fluorite	1	1	1	-	1	1	-	1
Apatite	-	-	1	-	-	1	1	1

* For convenience the ranges in percentages have been replaced by single numbers as follows: 1 = 0-2%, 2 = 2-5%, 3 = 5-10%, 4 = 10-15%, 5 = 15-20%, 6 = 20-30%, 7 = 30-40%, 8 = 40-50%, 9 = 50-75%, 10 = 75-100%.

TABLE 5. HEAVY MINERALS IDENTIFIED IN THE FINE AND VERY FINE SAND (.25-.05 mm.) SEPARATES OF RESIDUAL GRANITE PROFILE

Minerals	Sample Number							
	1	2	3	4	5	6	7	8
	Depth in Inches							
	0-4	4-10	10-18	18-24	24-30	26	24-30	26
Magnetite	3*	3	4	5	7	7	8	9
Ilmenite	4	3	3	2	2	2	2	2
Hematite	7	7	6	5	5	5	3	2
Limonite	2	2	2	2	2	2	-	-
Biotite	-	-	-	2	2	2	2	3
Hornblende	-	1	3	3	4	5	5	5
Zircon	3	3	3	2	2	2	1	1
Epidote	4	4	4	3	3	2	2	1
Fluorite	2	2	2	2	1	2	2	2
Apatite	2	2	1	2	1	2	1	2
Garnet	-	1	-	1	1	1	1	1
Pyrite	-	-	-	-	-	-	-	1
Tourmaline	2	1	2	1	1	1	1	1
Rutile	1	-	1	1	-	1	1	1
Titanite	1	1	1	1	1	1	1	1

* For convenience the ranges in percentages have been replaced by single numbers as follows: 1 = 0-2%, 2 = 2-5%, 3 = 5-10%, 4 = 10-15%, 5 = 15-20%, 6 = 20-30%, 7 = 30-40%, 8 = 40-50%, 9 = 50-75%, 10 = 75-100%.

TABLE 6. HEAVY MINERALS IDENTIFIED IN THE COARSE SILT
(.05-.02 mm.) SEPARATES OF RESIDUAL GRANITE PROFILE

Minerals	Sample Number							
	1	2	3	4	5	6	7	8
	Depth in Inches							
	0-4	4-10	10-18	18-24	24-30	26	24-30	26
Magnetite	5*	4	5	6	6	6	7	7
Ilmenite	5	4	2	2	2	2	2	2
Hematite	6	6	6	5	4	4	4	3
Limonite	4	4	3	3	3	2	1	1
Biotite	-	-	-	-	1	1	2	2
Hornblende	-	-	2	3	3	3	4	4
Zircon	4	3	4	3	3	3	3	2
Epidote	4	4	4	4	3	3	2	2
Fluorite	-	-	1	1	1	1	2	2
Apatite	-	1	1	2	1	2	2	2
Garnet	1	1	1	1	1	1	1	1
Pyrite	-	-	-	-	-	-	-	-
Tourmaline	2	2	2	1	1	1	1	1
Rutile	1	1	1	1	1	1	1	1
Titanite	1	1	1	1	1	1	1	1

* For convenience the ranges in percentages have been replaced by single num-
bers as follows: 1 = 0-2%, 2 = 2-5%, 3 = 5-10%, 4 = 10-15%, 5 = 15-20%,
6 = 20-30%, 7 = 30-40%, 8 = 40-50%, 9 = 50-75%, 10 = 75-100%.

Residual Diabase Soil.—The results of the quantitative heavy
liquid separations of the various separates are expressed in Table 7.

TABLE 7. DISTRIBUTION OF HEAVY MINERALS IN THE SAND FRACTIONS
OF THE RESIDUAL DIABASE SOIL

Sample Number	Depth (Inches)	Percentages of Fractions				Percentages of Whole Soil				
		>.5mm	.5-.25 mm	.25-.05 mm	.05-.02 mm	>.5mm	.5-.25 mm	.25-.05 mm	.05-.02 mm	Total >.02 mm
1	0-5	83.4	89.1	72.8	10.7	1.08	3.54	5.53	3.63	13.78
2	5-9	93.4	89.3	68.4	9.0	0.73	2.07	2.76	2.36	7.92
3	9-16	90.9	89.2	61.9	11.5	1.43	3.41	3.63	2.60	11.07
4	16-21	81.0	87.6	54.1	15.1	3.24	5.92	2.93	3.24	15.33
5	21-25	84.3	85.4	48.5	16.0	7.13	6.59	5.26	3.06	22.04
6	25-33	92.4	83.0	38.5	10.7	4.42	5.85	4.47	2.06	16.80
7	33-47	92.8	77.1	23.2	5.2	3.65	6.27	3.48	1.15	14.55
8	47-60	65.3	56.9	26.0	5.9	6.48	9.66	5.84	1.27	23.25

The occurrence of a high percentage of heavy minerals in the residual diabase soil necessitated further fractionation. Because of the range in specific gravity of the mineral constituents, additional heavy liquid separations were not practical. Their identification and counting were facilitated by a separation on the basis of their magnetic properties into highly magnetic, moderately magnetic, and non-magnetic minerals (Table 8).

TABLE 8. MAGNETIC FRACTIONATION OF THE HEAVY MINERALS OF THE RESIDUAL DIABASE SOIL

Sample No.	Depth in In.	>.5 mm. Magnetism			.5-.25 mm. Magnetism			.25-.05 mm Magnetism			.05-.02 mm Magnetism		
		Strong %	Moderate %	No %	Strong %	Moderate %	No %	Strong %	Moderate %	No %	Strong %	Moderate %	No %
1	0-5	35.9	35.2	28.9	59.5	28.9	11.6	48.6	42.3	9.1	5.5	43.7	50.8
2	5-9	44.3	35.0	20.7	68.6	22.9	8.4	57.9	35.8	6.3	4.8	42.5	52.7
3	9-16	43.8	35.3	20.9	60.8	30.9	8.4	62.9	28.2	8.9	5.4	50.7	43.9
4	16-21	34.9	38.7	26.4	71.5	17.0	11.5	64.1	25.7	10.1	7.8	34.9	57.3
5	21-25	29.3	26.4	44.4	61.0	21.1	17.9	53.6	33.1	13.3	7.5	36.8	55.7
6	25-33	42.2	41.7	16.1	67.3	24.0	8.7	59.6	24.7	15.6	9.3	36.2	54.5
7	33-47	69.6	18.7	11.7	47.0	39.4	13.7	42.9	34.9	22.2	9.7	36.9	53.4
8	47-60	61.6	21.4	17.1	43.2	33.8	23.0	42.8	31.6	25.6	8.5	43.4	48.1

Coarse Sand.—In the coarse sand fractions, the individual particles are essentially aggregates of various sized crystals of feldspar and ferromagnesian minerals with small quantities of accessory minerals. The high proportion of strongly magnetic minerals in the lower horizons is attributed to the dominance of aggregates at these depths. Examination of the minerals in the horizon at a depth of 33-47 inches reveals a zone of intensive weathering. Brown and reddish brown limonite coatings on the primary crystals are common. The decomposition of augite to secondary hornblende and the release of iron oxides emphasize the rate of breakdown in this horizon. An analysis of this secondary hornblende shows elongated, fibrous grains of variable green color. The crystals exhibit strong pleochroism from deep blue-green to pale yellowish green, and have an extinction angle of 11°. Secondary iron oxides are common associates of the amphibole.

The aggregates of the highly magnetic separate are dominated by magnetite and ilmenite with smaller quantities of augite and its secondary decomposition products: hornblende, hematite, epidote, and chlorite. In the moderately magnetic fraction augite assumes the dominant position in the aggregates with a corresponding decrease of iron oxides. The rapid rate of decomposition of the secondary hornblende is emphasized by a drop in percentage from 18.0 at a depth of 16-21″ to 5.4% in the surface soil. The aggregate of the non-magnetic fraction include relatively large proportions of plagioclase feldspar. Small percentages of concretions are present in the upper horizons.

Medium Sand (Table 9).—The proportion of aggregates in the medium sand fraction is too large to insure accuracy in correlation studies in this separate. However, general interpretations may be made. The accumulation of the iron oxide minerals in the upper horizons of the profile is explained by the additional supply of secondary constituents from the weathering of the ferromagnesian minerals and also by their resistance to weathering. The weathering of the augite is reflected in the increased percentage of its decomposition products, hornblende and epidote, in the A and B horizons. Concretions exist to a depth of 25 inches, but are most abundant in the surface soil.

TABLE 9. DISTRIBUTION OF HEAVY MINERALS IN THE MEDIUM
SAND (.5-.25 mm.) SEPARATE OF RESIDUAL DIABASE
SOIL (PERCENT OF FRACTION)

Sample Number	1	2	3	4	5	6	7	8
Depth in Inches	0-5	5-9	9-16	16-21	21-25	25-33	33-47	47-60
Minerals	%	%	%	%	%	%	%	%
Magnetite and Ilmenite	52.8	55.4	52.2	52.7	39.7	22.9	21.1	20.9
Hematite	8.9	10.8	9.2	10.2	6.3	3.7	2.5	0.0
Augite	9.8	9.4	16.7	7.3	14.8	10.3	25.7	16.5
Green Hornblende and Augite	3.7	3.4	4.3	3.7	3.5	2.3	0.8	0.7
Epidote	1.1	0.8	1.0	1.0	1.1	0.4	0.0	0.0
Concretions	8.0	3.9	3.7	3.1	1.1	0.0	0.0	0.0
Aggregates of Magnetite* Augite Ilmenite Hematite Feldspar	7.3	12.3	9.0	16.3	23.0	44.1	27.8	26.6
Aggregates of Augite* Ilmenite Feldspar	4.5	0.9	1.7	2.0	2.9	12.9	18.9	14.2
Aggregates of Augite* Feldspar	3.3	2.5	1.6	2.6	5.1	1.2	3.2	16.1
Aggregates of Feldspar* Augite	0.6	0.7	0.6	1.2	2.6	2.3	1.9	5.0

* Minerals listed in order of abundance

Fine and Very Fine Sand (Table 10).—The smaller proportions of aggregates in the upper horizons makes this separate more suitable for interpretations based on frequency of mineral occurrence. The general relationships presented from studies of the coarser fraction receive confirmation. An accumulation of biotite in the B_2 and upper C horizons may be explained by attributing to the mica a secondary origin. Its scarcity in the upper horizons of the profile indicates the ease with which it is weathered.

TABLE 10. DISTRIBUTION OF HEAVY MINERALS IN THE FINE AND
VERY FINE SAND (.25-.05 mm.) SEPARATE OF RESIDUAL
DIABASE SOIL (PERCENT OF FRACTION)

Sample Number	1	2	3	4	5	6	7	8
Depth in Inches	0-5	5-9	9-16	16-21	21-25	25-33	33-47	47-60
Minerals	%	%	%	%	%	%	%	%
Magnetite and Ilmenite	62.9	58.3	61.8	54.8	47.1	38.6	14.2	12.0
Hematite	9.5	5.7	11.1	10.5	10.5	7.5	3.0	3.0
Augite	14.5	11.5	10.1	9.3	11.3	9.5	8.3	5.8
Green Hornblende and Augite	2.4	1.8	2.2	2.8	3.0	3.0	3.0	1.6
Epidote	0.7	1.1	0.7	0.5	0.7	0.7	0.3	0.0
Concretions	7.2	15.2	5.7	4.5	4.0	2.0	0.1	0.0
Aggregates of Magnetite* Augite Ilmenite Hematite Feldspar	0.7	3.7	3.7	8.7	7.6	23.2	29.3	30.0
Aggregates of Augite* Ilmenite Feldspar	1.2	1.6	1.4	2.3	3.7	4.0	25.8	24.5
Aggregates of Augite* Feldspar	0.8	1.0	1.2	2.9	5.6	8.4	13.9	21.5
Biotite	0.1	0.1	1.8	3.6	5.3	2.6	2.0	1.4

* Minerals listed in order of abundance

Coarse Silt (Table 11).—This soil profile offers an excellent opportunity for the use of quantitative petrographic methods to formulate the processes of rock weathering and of soil formation. The very fine sand fraction is especially adapted because of the quantities of heavy minerals and the variety of minerals in the suite.

TABLE 11. DISTRIBUTION OF HEAVY MINERALS IN THE COARSE SILT
(.05-.02 mm.) SEPARATE OF RESIDUAL DIABASE SOIL
(PERCENT OF FRACTION)

Sample Number	1	2	3	4	5	6	7	8
Depth in Inches	0-5	5-9	9-16	16-21	21-25	25-33	33-47	47-60
Minerals	%	%	%	%	%	%	%	%
Augite	1.5	1.3	1.2	4.3	2.8	5.4	13.9	15.5
Biotite	2.1	1.1	1.4	3.2	3.4	3.3	4.1	2.9
Hornblende	7.9	6.1	12.9	21.9	23.3	23.9	27.7	29.4
Olivine	< 0.1	0.0	0.0	0.1	0.1	0.2	0.3	0.6
Black opaque	48.1	51.5	54.6	38.2	38.3	36.9	27.2	21.4
Magnetite	5.4	4.7	5.2	7.6	6.9	7.2	4.7	4.0
Limonite	4.2	11.9	5.7	5.2	3.2	4.8	2.1	4.3
Hematite	3.6	2.7	3.3	4.1	4.9	4.8	4.6	7.5
Goethite	0.1	0.2	< 0.1	< 0.1	< 0.1	0.1	< 0.1	< 0.1
Epidote	5.5	6.9	3.5	4.2	3.5	3.7	1.3	1.2
Zircon	1.6	3.8	1.2	1.2	0.8	0.7	0.3	0.2
Tourmaline	1.7	2.4	1.5	1.0	0.9	0.6	0.3	0.4
Rutile	0.5	0.4	0.3	0.3	0.2	0.3	0.1	0.2
Garnet	0.2	0.1	0.1	< 0.1	0.2	0.2	0.2	0.2
Anatase	0.8	1.0	0.3	0.3	0.1	0.1	< 0.1	<0.1
Apatite	0.3	0.3	0.5	0.6	0.7	0.7	0.8	2.3
Quartz	11.5	3.2	4.0	3.3	2.2	0.7	< 0.1	0.0
Feldspar	3.5	1.0	1.4	1.6	6.2	3.0	7.9	4.9
Fluorite	0.2	0.1	0.2	0.2	0.1	0.1	< 0.1	0.0
Chlorite	0.1	0.1	0.2	0.3	0.6	2.0	5.0	4.5

Over 18,200 mineral grains in this fraction alone were counted to make the microscopic analysis statistically significant.

The ratios of the relative proportions of the highly resistant minerals, for example tourmaline and zircon, may be used to establish the constancy of the parent material from which the soil was weathered. The presence of a continuous change in percentage of mineral constituents and in size distribution of particles is evidence to show that this soil weathered from diabase similar to that presented in the thin section studies. When the ratio between two mineral species remains constant throughout the horizons of the soil profile, the relative rates of weathering of the other mineral species may be obtained. Olivine decomposes very rapidly, verifying observations in the thin section studies. From the percentages of augite and hornblende in the various horizons one might conclude that augite weathered more rapidly than hornblende. However, the weathering of the hornblende involves that originally present in the C horizon and that formed from the decomposition of the augite. Consequently hornblende must be classified as a mineral that also weathers readily under the climatic conditions given. The weathering of biotite, the iron oxides and epidote is similarly complicated by their appearance in both primary and secondary forms. The accumulation of rutile and anatase shows the resistance of these titanium minerals to weathering. The appearance of the crystals of garnets and their frequency of occurrence in the various horizons

show these minerals to be somewhat weathered.   Apatite, and its resistance to weathering, have been the subject for considerable debate.   Goldfish (6) reports a slight accumulation of apatite in the weathered Medford diabase.   In the present instance the decrease in amount in the upper horizons of the residual soil indicates distinct weathering.   The presence of quartz and feldspar in the heavy fraction may be attributed to inclusions of heavy minerals.

Discussion of Heavy Mineral Studies

As previously pointed out, the weathering of the granite porphyry is but little influenced by the heavy minerals, which are present only in small amount.   The most remarkable fact shown in these studies is the formation of epidote and its subsequent resistance to weathering.   In this way calcium is locked up in a practically non-available form.   As regards the use of other resistant heavy minerals such as zircon as immobile indicators of soil formation processes, the determinations here recorded are probably at present inadequate. There is a possibility that the weathering of other minerals liberates inclusions of zircon.   The marked accumulation of zircon shown, for instance, in Table 11, may be due in part of this cause and the same may be true of the tourmaline.   Chemical determinations of zirconium and of boron on the total sand and silt fractions would probably give a more reliable index.

In spite of the long period of weathering to which the rocks have been subjected, some of the most easily weathered minerals are still to be found in the surface soil; for instance, augite is still present in the sand fractions of the diabase soil.   This illustrates the great importance of the factor of physical accessibility.   On chemical grounds alone its complete breakdown might have been anticipated, but the compact nature of many of the grains and their small specific surface have resulted in their preservation.

Mineralogical Analyses of the Light Fractions

In most mineralogical studies, the light minerals have been neglected in favor of the more interesting heavy minerals.   The classic work of Mackie (16) on "The Sands and Sandstones of Eastern Moray" is an exception.   Recent research is placing more emphasis on the analysis of the light fractions.   Jeffries and White (12, 13) present evidence of changes in composition of the feldspars in their studies of a Hagerstown soil profile.   Graham's studies (7) stress the importance of the silt fractions in plant nutrition, and such studies necessitate the complete analysis of the mineral constituents.

Residual Granite Soil

In the Missouri granite, the specific gravity separations of the larger sized fractions left the light fraction composed essentially of quartz and orthoclase.   The rates of weathering of these two minerals were brought out very effectively in the quartz-feldspar

ratios of the various fractions of the different horizons of the soil profile. Counts ranging from 250 to 800 grains were made and the results are expressed in Table 12 as percentages of quartz in the light fraction.

Feldspar.—The prismatic orthoclase crystals of sample 8 first lost their vitreous luster. Their color also changed quickly to a dull shade of pink. Solution altered the sharply-edged, prismatic crystals to more rounded, irregularly shaped grains. The transformations given are represented in Figure 9a by crystals in the various horizons from the parent material to the surface soil.

The large unweathered crystal on the left represents the type of crystal found in the unweathered parent material. Its vitreous luster and light pink color are very distinct. The appearance of the grains changed rapidly as weathering began. Chlorite and secondary epidote from associated ferromagnesian minerals gave the grains a greenish cast. The two grains to the right of the large crystal show the chlorite and epidote as dark stains. The prevalence of yellowish brown iron oxide coatings on the crystals in the upper horizons of the soil profile emphasize the low stability of the epidote and chlorite. The three crystals on the right present a typical corroded appearance with the surfaces exhibiting an abundance of secondary products including secondary micas, clay minerals, and iron oxides.

TABLE 12. THE DISTRIBUTION OF QUARTZ IN THE RESIDUAL GRANITE PROFILE
(PERCENT OF LIGHT MINERAL FRACTIONS SP. GR.<2.80)

Sample Number	Depth in Inches	Sands			Coarse Silts	
		>.5 mm. %	.5-.25 mm. %	.25-.05 mm. %	.05-.02 mm. %	.02-.005 mm.* %
1	0-4	77.9	69.7	77.0	63.6	60.2
2	4-10	83.8	68.5	72.3	62.3	56.1
3	10-18	68.5	61.8	64.5	62.2	45.3
4	18-24	46.9	33.8	46.7	59.1	31.3
5	24-30**	41.1	29.9	24.4	58.4	17.9
6	26	41.8	32.9	29.4	58.8	19.6
7	24-30	29.2	22.6	28.8	41.9	9.8
8	26	27.5	20.4	21.9	40.7	9.7

* Heavy minerals not removed.

Sample Number	Depth (Inches)	(Percentages of the whole soil)					
		>.5 mm.	.5-.25 mm.	.25-.05 mm.	.05-.02 mm.	.02-.005 mm.	Total >.005 mm.
1	0-4	1.76	0.76	1.39	16.74	26.71	47.36
2	4-10	0.86	0.49	0.63	13.12	24.51	39.61
3	10-18	0.36	0.36	0.44	7.85	16.65	25.66
4	18-24	1.01	0.39	0.69	8.82	11.14	22.05
5	24-30**	4.30	1.07	0.63	14.85	4.86	25.71
6	26	3.36	1.20	0.97	12.70	5.85	24.08
7	24-30	6.61	1.54	1.30	13.10	2.37	24.92
8	26	9.32	2.38	1.74	9.46	1.60	24.50

** 5 - Decomposed hull of weathered parent material
   6 - Partially decomposed hull enclosing unaltered granite
   7 - Crushed fragments of weathered parent material
   8 - Crushed fragments of unaltered granite

Fig. 9(a).—Photomicrograph of orthoclase crystals weathering.

Quartz.—The appearance of the quartz phenocrysts in the thin sections prompted a detailed study of the quartz grains in the residual soil. An explanation for their physical breakdown is given in the discussion of quartz grains in the thin section studies. The quartz occurs in shapeless, slightly turbid grains with sharply defined inclusions. The variations in shape with decrease in size is easily distinguished. The grains in the fractions larger than .25 mm. present varying degrees of roundness, while those below this limit are decidedly angular. Since roundness cannot be attributed to the transportation of the minerals in this profile, its explanation was found elsewhere. An examination of hand specimens of the unweathered parent material give, in many instances, partially rounded quartz phenocrysts. The penetration of the oxides of iron into the fracture planes of the quartz was very interesting to follow. Upon weathering of the ferromagnesian minerals and the consequent release of iron oxides and upon oxidation of the magnetite, films of limonite and hematite penetrated the quartz crystals.
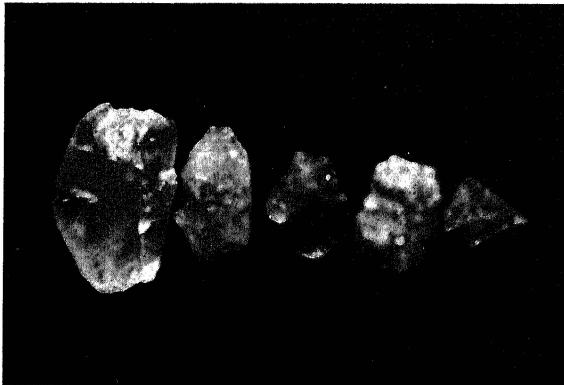
Fig. 9(b).—Photomicrograph of representative quartz crystals.

In Figure 9(b), the large crystal on the left shows the fracture planes

running in many directions. A portion of the center crystal was chipped, exposing a face covered with a film of iron oxide. The angularity of the smaller grain on the right is typical of the smaller fractions.

The large quantities of quartz in the parent material in the fraction .05-.02 mm. show the prevalence of this mineral in the ground mass. The increases in percentages of quartz in the upper horizons of the profile are not so pronounced as in the other fractions due to the correspondingly smaller amounts of orthoclase originally present. The variation in quartz content with its increase in the upper soil horizons is undoubtedly due to the weathering of the feldspars and the transportation of large amounts of the resultant clay minerals to the B horizon.

Figure 10 represents graphically the distribution of quartz, feldspar, and clay in the soil profile.
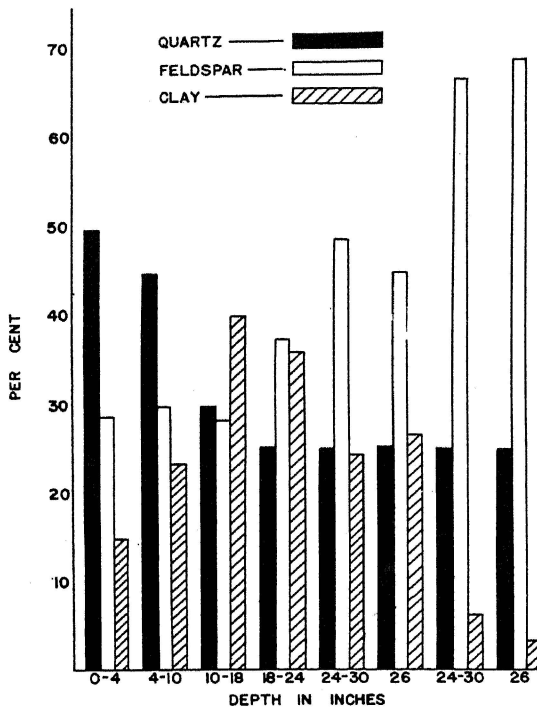
Fig. 10.—Distribution of quartz and feldspar in the sands and coarse silt, and the clay in the residual granite soil.

Residual Diabase Soil (Table 13)

The specific gravity separations isolated the feldspars, secondary quartz and chalcedony, mica, and a majority of the concretions from the abundant suite of heavy minerals. Quantitative counts of the mineral constituents in the various horizons emphasize their extreme

variation in susceptibility to weathering. The accumulation of the quartz and chalcedony in the upper horizons of the profile from less than 2% to more than 24% stresses the rapid rate at which the plagioclase feldspars are weathered. A comparison of the quartz-feldspar ratios of the two soils shows conclusively that calcium feldspars weather more rapidly than the potash feldspars. The occurrence of a secondary biotite in the lower horizons of the profile is attributed to the decomposition of the ferromagnesian minerals. Its scarcity in the more highly weathered horizons indicates the ease with which this mineral is decomposed.

TABLE 13. DISTRIBUTION OF LIGHT MINERALS (Sp. Gr.<2.80) IN SAND FRACTIONS OF RESIDUAL DIABASE SOIL

Sample Number	Depth in Inches	>.5 mm.					.5-.25 mm.				.25-.05 mm.					.05-.02 mm.			
		Feldspar*	Feldspar**	Quartz	Chalcedony	Concretions	Feldspar	Quartz	Chalcedony	Concretions	Mica	Feldspar	Quartz	Chalcedony	Concretions	Mica	Feldspar	Quartz & Chalcedony	Chlorite
1	0-5	24.5	28.1	21.1	7.0	19.3	34.8	13.7	24.4	27.1	0.5	37.1	45.1	8.6	8.8	1.1	19.5	77.6	1.8
2	5-9	5.9	41.2	29.4	5.9	17.7	38.2	17.8	19.7	24.2	0.4	41.4	33.0	7.6	17.5	3.0	22.6	72.0	2.4
3	9-16	16.7	52.4	21.4	4.8	4.8	70.7	9.4	11.1	8.8	0.9	48.5	27.5	13.1	9.9	3.8	16.7	76.6	2.9
4	16-21	16.9	60.4	14.3	3.9	4.6	74.7	9.6	8.4	7.4	2.9	53.0	22.2	13.8	8.1	7.0	22.7	66.6	3.6
5	21-25	33.1	57.4	5.2	4.4	0.0	77.7	9.6	8.3	4.4	5.0	64.4	14.4	12.6	3.6	11.1	32.2	52.2	4.5
6	25-33	67.7	27.9	0.6	3.8	0.0	94.0	0.6	1.8	3.6	12.5	62.5	8.8	16.0	0.2	31.4	35.2	31.5	1.5
7	33-47	47.0	51.0	1.0	1.0	0.0	97.8	0.3	1.5	0.5	31.1	53.0	5.3	10.6	0.1	39.3	54.0	5.4	1.3
8	47-60	97.2	2.8	0.0	0.0	0.0	97.8	0.2	2.0	0.0	14.9	78.4	3.0	3.7	0.0	16.6	81.0	2.1	0.3

* Fresh Feldspar
** Weathered Feldspar

Feldspar.—The alteration of the lath-shaped crystals of plagioclase feldspar is reflected in the development of nests of rather coarse flakes of a micaceous mineral of high birefringence. The optical properties of this micaceous mineral check very closely with those of paragonite. The change in the dominance of the high calcium labradorite to the more sodic members of the plagioclase series from the weathering rock to the more highly weathered soil indicates the ease with which these minerals lose their calcium. The residual sodic feldspars are crowded with dust-like inclusions of secondary clay minerals and highly sericitized with variously oriented micaceous flakes. Kloos (14) presents chemical data to suggest the transformation of laboradorite to albite and one of the zeolites.

Quartz.—The occurrence of quartz in as basic a rock as the Missouri diabase is not common. However, it does exist in very small quantities in transparent slightly smoky crystals up to 1 mm. in diameter. Many crystals show hexagonal prisms terminated by symmetrical hexagonal pyramids. These euhedral crystals are also characteristic of secondary forms. The quartz is fractured and the penetration of the oxides of iron are the same as described in the residual granite soil.

Chalcedony.—This cryptocrystalline variety of quartz occurs in cream colored crystals with a waxy or greasy luster up to 1 mm. in diameter. They display the characteristic banded structure, frequently attributed to

the alternation of layers of quartz, chalcedony, and opal. A comparison of the rates of accumulation of quartz and chalcedony show their resistance to weathering to be approximately the same under the climatic conditions of the Ozarks.

Mica.—Secondary mica exists in light brown, strongly pleochroic flakes and scales—a constant companion of the secondary hornblende. The bluish green colors in the center of the crystals of hornblende, transform into turbid, weak yellowish green colors at the edges, reflecting an accumulation of small flakes of secondary mica. Calcite exists in minute grains as an end product in the transformation of hornblende to mica. The flakes of mica are isolated upon complete decomposition of the hornblende, and the position of large quantities in the lower horizons of the soil profile necessitates a relatively rapid transformation. The breakdown of the mica to the resultant clay minerals is an equally rapid process. Residual products of silicates intermediate between the primary and better-known secondary minerals are to be expected. Limitations in facilities for studying the finer particles have restricted progress in this field. The initial changes in weathering of the mica are evidenced by a changing of the brown color to a yellowish green with the preservation of the optical properties. The process of bleaching essentially appears to be a leaching of the iron, which begins at the periphery and proceeds irregularly to the center of the flakes. On hydrolysis considerable iron and potassium are replaced by hydrogen in the crystal lattice. With the loss of iron the indices of refraction and the specific gravity of the crystals are lowered. Cranner (4), in his vegetation investigations concluded that plants were able to obtain considerable quantities of potassium from biotite and sericite. Biotite transformations to green chlorite are common. Among the flakes of biotite and chlorite are mixed lens-shaped masses of carbonates, quartz, and iron oxides.

Chlorite.—Chlorite exists in small quantities in the very fine sand fraction. Often small grains of iron oxide are so completely dispersed among the chloritic products that the mass exhibits a red metallic luster. In some cases the chlorite is pseudomorphic, with perfect retention of shape of the original crystals. These cases are rare in the more highly weathered horizons of the soil profile. It is apparent that chlorite weathers easily because new sources are available from decomposing ferromagnesian minerals and yet no accumulation occurs in the more highly weathered surface soil.

Concretions.—The abundance of concretions in the surface soil justifies special consideration. They are very similar in form to those described in the residual granite soil. The differences occur chiefly in the inclusions of mineral constituents. Thin sections of concretions formed in the residual granite soil display a very large proportion of quartz cemented by the oxides of iron. The concretions in the residual diabase soil have a diversity of constituents as inclusions, essentially because of the wide variety in the suite of minerals.

Figure 11 represents graphically the distribution of quartz, chalcedony, feldspar, clay and mica in the soil profile.

Discussion

The weathering of the light minerals brings out some striking differences between the two rocks and the soils derived from them. The granitic soil shows a marked physical breakdown of quartz but there is little accumulation of secondary silica. The higher figures for quartz in the 0-5 and 5-9 inch samples are probably caused by the loss of clay by downward movement. The basic

igneous rock shows an abundant accumulation of chalcedony. If we neglect the ferromagnesian minerals for the moment, we are faced with the apparent paradox that feldspar with 6 Si O_2 per unit cell decomposes leaving no free silica whereas that with 5 Si O_2 leaves quantities of chalcedony. There are, however, too many undetermined factors in the situation to allow of facile generalizations.
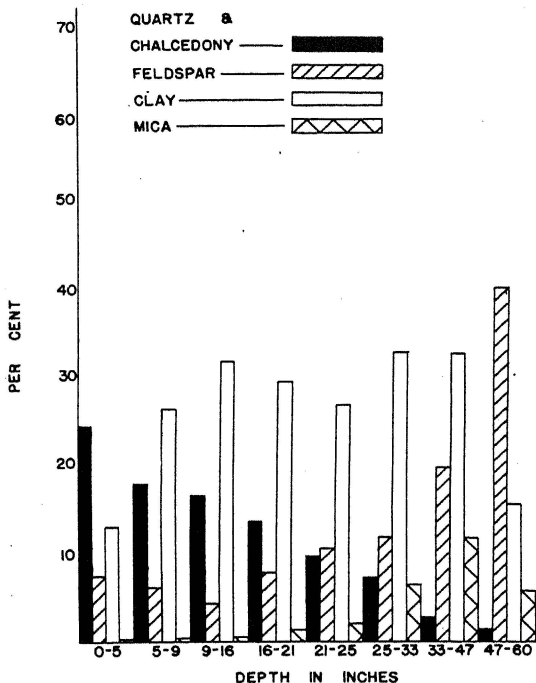

Fig. 11.—Distribution of quartz and chalcedony, feldspar and mica in the sands and coarse silt, and the clay in the residual diabase profile.

MINERALOGICAL ANALYSES OF THE FINE SILTS AND CLAYS

The ordinary mineralogical methods described in Milner's "Sedimentary Petrography" (23) proved to be adequate for analysis of the sand fractions and the coarse silt. To complete the story of the weathering of masses of rocks to soil necessitates the examination of the finer products of decomposition. In order to study the finer separates, it is essential to fractionate with narrow limits in range of size. The gravity sedimentation methods used for separating the sands and the silts prove inadequate for further subdivision of the clay fraction. Centrifugal methods described by Marshall (18) were used for further fractionation.

The identification of particles less than 20μ in size centers around the determinations of refractive indices, birefringence, and specific gravity. The size of the particles prohibits the use of interference figures in classification.

Quantitative counts of quartz and feldspar were limited to the crystals above 5μ. In the 20-5μ fraction the quartz exists in distinctly angular forms. Euhedral crystals were exceptionally rare. The feldspar of this fraction show evidence of a high degree of weathering. It is evident that the increased surface of these smaller particles would result in a more rapid transition to the alteration products. This is strikingly shown by the larger proportion of quartz. The clay minerals first make their appearance in the smaller sized particles of this fraction.

Index of Refraction Studies

The identification of particles smaller than 5μ necessitates new methods of analysis. The refractive index determinations involve the use of dark ground methods of illumination. Particles with refractive indices slightly lower than the liquid emit a purplish or bluish light while those with indices slightly higher give a yellowish or light brown light. The immersion liquid used was potassium mercuric iodide. Mixtures of a dilute suspension of particles in water with appropriate quantities of saturated potassium mercuric iodide give the required refractive index. The correct proportions of the two liquids are given by Marshall (19) in "Mineralogical Methods for the Study of Silts and Clays."

Counts were made of particles in representative fields and the number recorded both above and below the immersion media. Special precautions were taken in the counts of particles mounted in media of indices much different from the refractive indices of the bulk of the particles. The unreliable color effects which occur in these instances limit the accuracy. A comparison of the series of slides gives an approximate percentage of the particles within chosen ranges of indices of refraction.

Residual Granite Soil.—The results are expressed in percentages in Tables 14 and 15.

TABLE 14. DISTRIBUTION OF PARTICLES ACCORDING TO RANGES IN REFRACTIVE INDICES (PERCENT OF SAMPLE)
FRACTION: 5 - 2μ RESIDUAL GRANITE SOIL

Sample Number	Ranges in Refractive Indices						
	<1.527	1.527- -1.536	1.536- 1.545	1.545- 1.553	1.553- 1.568	>1.568	
	%	%	%	%	%	%	%
1	1	40	25	25		10	
2	10	45	15	20		10	
3	21	32	15	10	11		11
4	23	27	20	4	11		15
5	19	27	4	25		21	
6	26	32	11	6	8		17
7	44	8	5	20	9		14
8	40	9	5	20		26	

TABLE 15. DISTRIBUTION OF PARTICLES ACCORDING TO RANGES
IN REFRACTIVE INDICES (PERCENT OF SAMPLE)
FRACTION: 2 - 0.5μ RESIDUAL GRANITE SOIL

Sample Number	Ranges in Refractive Indices						
	<1.527	1.527-1.545	1.545-1.568	1.568-1.574	1.574-1.586	>1.586	
	%	%	%	%	%	%	%
1	0	15	27	33		25	
2	1	20	21	20	23		15
3	1	10	38	21	22		8
4	7	13	35	29	7		9
5	11	7	37	12	13		30
6	11	9	39	26	6		9
7	50	4	27		2		12
8	57	5	27		2		9

Studies of the indices of refraction of the 5-2μ separate show the tendency for an accumulation of quartz (R.I. 1.545-1.553) and a decrease in orthoclase (R.I. 1.527) from the parent material to the surface soil. The percent of feldspars in the weathering parent material (Samples 7 and 8) is nearly double that in the weathering hulls and the B and C horizons. In the A horizon, a zone of intensive weathering, the transformation of feldspar to the clay minerals is nearly complete. The wide range in the indices of the minerals here indicates a heterogeneous mixture.

The same tendency is seen in the 2μ-0.5μ fraction where the decrease in the feldspar is even sharper. The increase in specific surface ensures a rapid disappearance of the finely divided orthoclase.

Index of Refraction studies of <.5μ separate.—Analyses of the aggregates of smaller particles give an approximate value for the refractive index of the bulk of the material. The aggregation of particles of different refractive indices makes accurate counting impossible. Further fractionation of the <.5μ fraction would aid in identification because of the probability of obtaining more homogeneous systems.

The particles were mounted in a series of liquids with indices identical with those in Table 15. The one exception was the insertion of a 1.553 liquid to check the presence of the smaller particles of quartz. A slight increase in the range 1.545-1.553 in the upper horizons of the profile indicates that small amounts of quartz exist in this fraction. The crushed parent material is essentially orthoclase. The more weathered sample, #7, showed slight increases in the particles with refractive indices ranging from 1.545 to 1.586. The soil brushed from the weathering parent material showed very pronounced effects of the presence of the initial weathering products of the ferromagnesian minerals. Of sample #5, 35-50% had indices

of refraction ranging from 1.545 to 1.568. Ten per cent of the
particles of this sample occur in the range 1.568-1.586. The B
horizon (10-24″) gave decreased amounts of particles of lower in-
dices and decided increases in the percentages of particles of higher
indices. Of samples #3 and #4, 70-80% gave mean indices of
1.565 with 30% occurring in the range 1.568-1.586. The surface soil
showed a marked decrease of the clay minerals of higher refractive
indices and an increase to 50% of particles with a mean index of
refraction of 1.540.

Residual Diabase Soil.—The results are expressed in percentages
in Tables 16 and 17.

TABLE 16. DISTRIBUTION OF PARTICLES IN THE RESIDUAL
DIABASE SOIL ACCORDING TO RANGES IN RE-
FRACTIVE INDICES FRACTION: 5 - 2 μ

Sample Number	Depth in Inches	Ranges in Refractive Indices						
		<1.527	1.527-1.544	1.544-1.553	1.553-1.640	1.640-1.650	1.650-1.710	>1.710
		%	%	%	%	%	%	%
1	0-5	9*	1	11	7	10	50	12
2	5-9	8	3	11	5	19	47	7
3	9-16	18	4	2	6	26	33	11
4	16-21	12	10	1	6	35	26	10
5	21-25	10	17	2	3	43	14	11
6	25-33	10	17	1	3	42	12	14
7	33-47	6	19	1	9	32	21	13
8	47-60	12	10	2	19	29	14	14

* Results expressed in per cent of sample

TABLE 17. DISTRIBUTION OF PARTICLES IN RESIDUAL DIABASE
SOIL ACCORDING TO RANGES IN REFRACTIVE INDICES
FRACTION: 2 - 0.5 μ

Sample Number	Depth in Inches	Ranges in Refractive Indices					
		<1.527	1.527-1.553	1.553-1.568	1.568-1.574	1.574-1.640	>1.640
		%	%	%	%	%	%
1	0-5	7*	7	19	21	32	15
2	5-9	8	10	30	9	31	12
3	9-16	9	19	26	14	15	17
4	16-21	9	22	23	5	29	13
5	21-25	9	17	31	6	30	8
6	25-33	11	6	32	8	29	15
7	33-47	8	9	31	16	25	11
8	47-60	10	6	26	27	22	9

* Results expressed in percent of sample

Studies of the fine silt show an abundance of hornblende and other secondary decomposition products of the ferromagnesian minerals. A slight accumulation of quartz is balanced by a decrease in the feldspars from the parent material to the surface soil. It is apparent that the high surface exposed per unit of mass limits the existance of the feldspars. The clay minerals, although present in this fraction, are overshadowed by the dominant chloritic decomposition products.

From Table 17 it is evident that the clay minerals dominate the 2-0.5μ fraction. The high proportion of minerals with indices of refraction ranging from 1.553 to 1.640 eliminates both halloysite and montmorillonite as the dominant clay mineral constituent. The range of indices shows small quantities of primary particles to exist in this size fraction. The constancy, throughout the profile, of particles with a mean refractive index 1.527 is difficult to explain. Microcline is a resistant potash feldspar but probably would not persist in such large quantities in small grains. Zeolites have been reported (25) in the weathering of diabase in Virginia. They may exist in the clay fraction of the Missouri soil but were not identified in the coarser fractions where optical properties could be determined with accuracy. The presence of considerable quantities of minerals with relatively high indices of refraction suggest the presence of chloritic products in addition to small quantities of heavy accessory minerals.

Index of refraction studies of $<.5\mu$ **separate.**—The range of indices of the particles still indicate small quantities of accessory minerals exist in the finer fractions. The accessory minerals are definitely in the minority and constitute $<10\%$ of the particles. Seventy-five to 80% of the particles fall within the range of 1.553 and 1.574.

Identification of the clay minerals on the basis of their refractive indices alone is somewhat precarious. Additional studies are desirable. However, the optical properties of the clays in these two profiles eliminate all clay minerals with the exception of kaolinite and iron rich beidellite.

Specific Gravity Studies

The mean specific gravity of the fractions was obtained by the use of the same heavy liquid. Bubbles of air were removed from the tubes containing the mixture of potassium mercuric iodic and clay suspension by means of a vacuum pump. A series of tubes of varying densities was set up for each fraction and the sedimentation of the coagulated clay was hastened by the use of a centrifuge.

Residual Granite Soil.—The mean specific gravity of the fractions is given in Table 18. The values obtained are consistent with the optical data.

Residual Diabase Soil.—The mean specific gravity of the fractions

is given in Table 19. The values obtained are similar to those of the clay from the granitic soil.

TABLE 18. MEAN SPECIFIC GRAVITY OF FINE SILT AND CLAY FRACTIONS OF THE RESIDUAL GRANITE SOIL

Sample Number	Depth in Inches	Size Range		
		$5 - 2\mu$	$2 - 0.5\mu$	$< 0.5\mu$
1	0-4	2.625	2.59	2.46
2	4-10	2.65	2.632	2.52
3	10-18	2.66	2.67	2.52
4	18-24	2.66	2.67	2.54
5	24-30	2.66	2.66	2.54
6	26	2.65	2.65	2.53
7	24-30	2.64	2.62	2.62
8	26	2.625	2.61	2.605

TABLE 19. MEAN SPECIFIC GRAVITY OF CLAY FRACTIONS OF THE RESIDUAL DIABASE SOIL

Sample Number	Depth in Inches	Size Range	
		$2 - 0.5\mu$	$< 0.5\mu$
1	0-5	2.63	2.50
2	5-9	2.66	2.52
3	9-16	2.66	2.53
4	16-21	2.67	2.51
5	21-25	2.63	2.50
6	25-33	2.62	2.53
7	33-47	2.58	2.52
8	47-60	2.59	2.52

Double Refraction Studies

The measurements of the double refraction of the clay particles depends upon their orientation in an electric field. The apparatus used for this measurement has been described by Marshall (17, 21), Coagulation of the H+-clays necessitated the use of very dilute suspensions (.000075 gm./cc.). Readings were obtained by using a larger cell, measuring 4.65 x 1.3 cm. The values of the double refraction were calculated from the following formula, using the mean of eight readings.

$$\frac{x}{180} \times \frac{\lambda}{1} \times \frac{d}{c} = \text{Double Refraction}$$

$x =$ phase angle of the double refraction
$\lambda =$ wave length of light
$1 =$ length of cell
$d =$ density of clay
$c =$ concentration in gms./cc.

To obtain maximum orientation of particles, a series of voltages were applied up to 1000 volts. Another series of experiments was run to determine the effect of the absorbed ions on the double refraction of the clay. The clay was electrodialized and titrated to a ph of 8.5 with the hydroxides of the cations Ca and Na. The results of this series of experiments are given in tables 20, 21 and 22.

TABLE 20. THE ELECTRICAL DOUBLE REFRACTION OF THE
CLAY OF THE RESIDUAL GRANITE SOIL, FRACTION:
$<0.5\mu$ H^+-system

Sample	Voltages			
Number	375	500	750	1000
1	.0108	.0126	.0140	.0141
2	.0125	.0137	.0146	.0149
3	.0140	.0155	.0170	.0170
4	.0132	.0148	.0173	.0174
5	.0147	.0163	.0178	.0177
6	.0067	.0072	.0073	.0073
7	.0063	.0086	.0102	.0103
8	.0035	.0037	.0044	.0046

TABLE 21. THE ELECTRICAL DOUBLE REFRACTION OF
THE CLAY OF THE RESIDUAL GRANITE SOIL, FRACTION:
$<0.5\mu$ Na^+-system

Sample	Voltages			
Number	375	500	750	1000
1	.0114	.0127	.0147	.0147
2	.0130	.0144	.0154	.0155
3	.0144	.0159	.0174	.0174
4	.0135	.0153	.0166	.0167
5	.0146	.0163	.0179	.0179
6	.0075	.0084	.0095	.0095
7	.0121	.0133	.0138	.0142
8	.0063	.0065	.0072	.0074

TABLE 22. THE ELECTRICAL DOUBLE REFRACTION OF
THE CLAY OF THE RESIDUAL GRANITE SOIL, FRACTION:
$<0.5\mu$ Ca^{++}-system

Sample	Voltages			
Number	375	500	750	1000
1	.0129	.0131	.0151	.0151
2	.0145	.0152	.0159	.0160
3	.0159	.0174	.0178	.0178
4	.0152	.0165	.0180	.0180
5	.0151	.0167	.0180	.0181
6	.0083	.0086	.0096	.0096
7	.0136	.0175	.0157	.0157
8	.0067	.0070	.0072	.0073

Measurements of the electrical double refraction of the $2\text{-}0.5\mu$ fraction proved to be only moderately satisfactory. The smaller angles and a less distinct position of extinction in the larger sized fractions limit the accuracy of their measurement. The unsatisfactory results are attributed to the depolarization of the incident beam of light by the larger particles. However, the low values obtained are entirely within the limits expected since the birefringence of quartz measures only .0044 and that of orthoclase slightly above. The presence of these two minerals in any measurable quantity would lower the values of the clay minerals.

Measurements of the smaller sized fraction proved to be much more satisfactory. A maximum orientation of particles occurred with an application of 750 volts. In comparing the double refraction at the higher voltages, an effort was made to control the temperature. The suspensions in the cell were replaced after each pair of readings. The series of experiments comparing the effect of the adsorbed cation on the double refraction of the clay show the divalent cation Ca^{++} to give the maximum readings. The clay on which the sodium was absorbed gave intermediate readings, while the values for the H^+-systems were consistently lower. The maximum values were obtained in the B horizon and these correspond to clays of the beidellite-montmorillonite groups.

Discussion.—The characterization of the fine fractions by refractive index, density and birefringence studies leads to the following conclusions.

In the case of the granite soil the major constituent is a member of the beidellite-nontronite series. The maximum birefriengence and index of refraction occurs in the clay fraction from the B horizon, suggesting a greater replacement of iron for aluminum. The data are consistent with the presence of some kaolinite and possibly also some sericite. Sample 5 at 24-30 inches contained a high proportion of material with higher refractive indices. This may have resulted from the presence of finely divided chlorites or epidote which finally disappear by weathering from the upper horizons.

As regards the diabase soil, the general results are surprisingly similar to those of the granite soil fractions.

Electron Microscope Studies

The search for methods of mineralogical characterization of the clay minerals results from the insufficiency in the characterization of soil colloids by chemical composition alone. The determination of optical properties by refined techniques was a definite step in the advancement of the knowledge of clays. Because of the limitations in the resolving power of the light microscopes, quantitative studies on shapes and structures of the finer particles were restricted. The development of the electron microscope has given a

new avenue of approach toward the more complete characterization of clay.

Recent research (11, 26) with the electron microscope in the field of clay mineralogy has yielded fruitful results. Magnification up to 100,000 reveal wide variations in structure. Many of the properties of the clays can be correlated with and interpreted on the basis of the visible structures.

In addition, the electron microscope reveals whether or not the dispersion techniques used were adequate (22). Good dispersion was obtained in the fractionation of the clay from both profiles.

The construction and operation of the electron microscope are described in current literature (11, 24, 31). The method of preparing specimens for microscopic study was the same as that used in a previous investigation (11).

Residual Granite Soil.—Studies with the electron microscope characterize the clay as essentially beidellite with varying proportions of micaceous minerals and a smaller proportion of quartz and the heavy minerals (Figures 12-21). The dominance of opaque minerals in the surface horizon indicates an accumulation of quartz and the heavy minerals in this highly weathered zone. (Figures 12-13). Two crystals in Figure 18 show the concentric structure, characteristic of secondary chalcedony. The thin plates in Figures 14 and 15 are characteristic of the micaceous minerals. The development of nests of minute opaque minerals, probably iron oxide, are characteristic of many of the secondary products of decomposition. This was a common observation in horizons 5 and 6 of the weathering parent material.

The dominating clay mineral exists as thin plates of no distinctive habit. These may be regarded as intermediate in morphology between the sharp angles and straight edges of kaolinite with its compact structure, and the "fluffy" appearance of montmorillonite which is caused by its open structure or its breakdown into very thin units. This intermediate character seems to be possessed only by beidellite.

An examination of the size of particles in each of the two separates indicate relatively good dispersion during fractionation. The presence of smaller particles in the 2-.5μ fraction, however, does emphasize some limitations in the techniques now used.

Electron Micrographs of Clay From

Residual Granite Soil
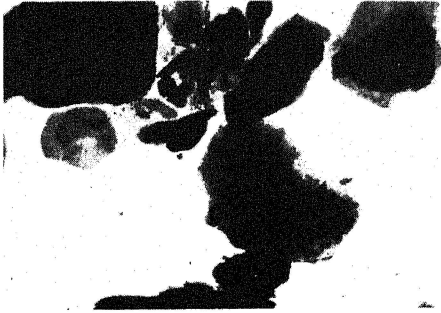
Fig. 12.—Residual granite soil. Depth 0-4″.
Fraction 2μ-0.5μ.

Fig. 13.—Residual granite soil. Depth 0-4″.
Fraction 2μ-0.5μ.
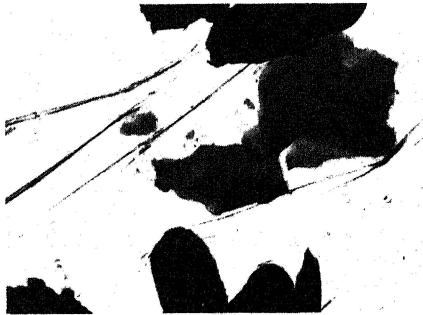
Fig. 14.—Residual granite soil. Depth 4-10″.
Fraction 2μ-0.5μ.

Fig. 15.—Residual granite soil. Depth 4-10″.
Fraction 2μ-0.5μ.
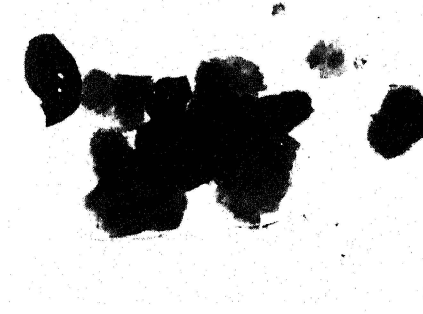
Fig. 16.—Residual granite soil. Depth 10-18″.
Fraction 2μ-0.5μ.
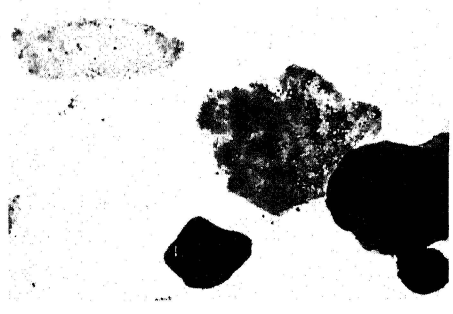
Fig. 17.—Residual granite soil. Depth 10-18″.
Fraction 2μ-0.5μ.

Electron Micrographs of Clay From

Residual Granite Soil
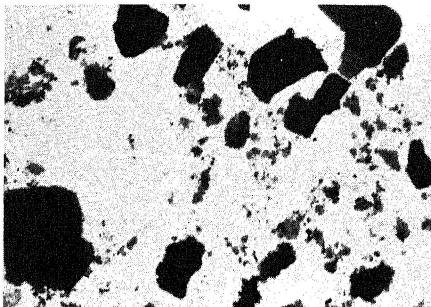
Fig. 18.—Residual granite soil. Depth 10-18". Fraction 2µ-0.5µ.
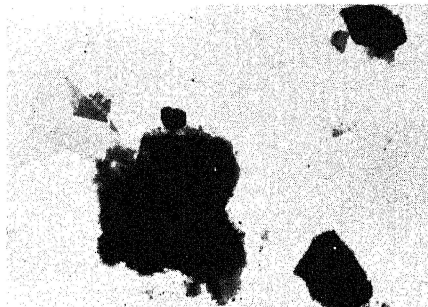
Fig. 19.—Residual granite soil. Depth 10-18" Fraction 2µ-0.5µ.
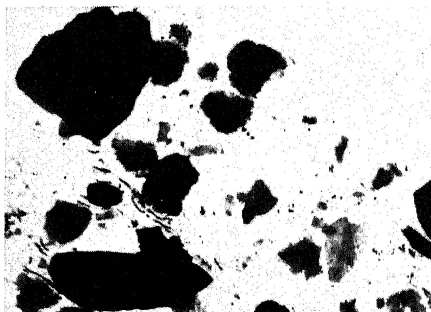
Fig. 20.—Residual granite soil. Depth 18-24". Fraction 2µ-0.5µ.
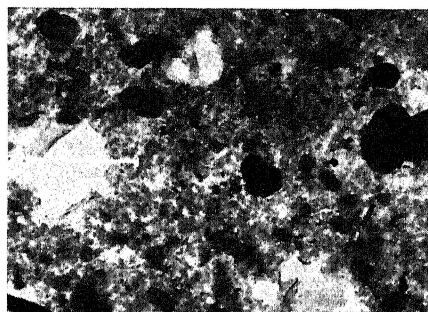
Fig. 21.—Residual granite soil. Depth 10-18". Fraction < 0.5µ.

Residual Diabase Soil.—The optical properties of the clay, as in the residual granite soil, characterize it as either beidellite or kaolinite.

2-.5µ Fraction: Figures 22 and 23 (0-5") show representative crystals of the surface soil. The sharply defined, opaque minerals resemble the quartz crystals studied. The micaceous clay minerals are very characteristic. Figure 23 (5-9") shows similar crystals, but also reveals the presence of smaller particles suggesting limitations in the dispersion technique used. Figure 23 (5-9") exhibits crystals of halloysite. The split character of the thin rods is typical of this particular type of clay mineral. Halloysite does not occur in large quantities in the residual clay but is present in minor amounts. Figures 26 (9-16") and 27 (16-21") show the characteristic thin plates in the lower horizons of the profile. The variations in density with an overlap of particles emphasize the extreme thinness of the structual units of this particular type of clay mineral. Figure 28 (16-21") shows an aggregate of smaller particles that was not dispersed and was fractionated in the upper size range of the

Electron Micrographs of Clay From

Residual Diabase Soil
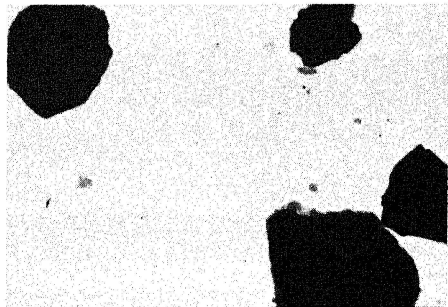
Fig. 22.—Residual diabase soil. Depth 0-5″.
Fraction 2μ-0.5μ.
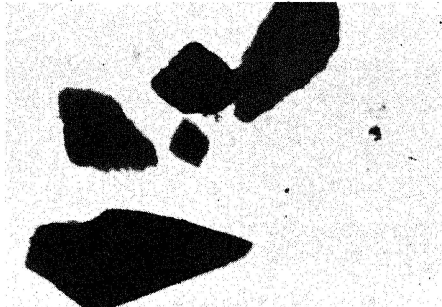
Fig. 23.—Residual diabase soil. Depth 0-5″.
Fraction 2μ-0.5μ.
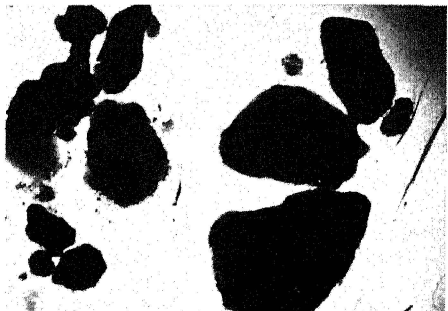
Fig. 24.—Residual diabase soil. Depth 5-9″.
Fraction 2μ-0.5μ.

Fig. 25.—Residual diabase soil. Depth 5-9″.
Fraction 2μ-0.5μ.
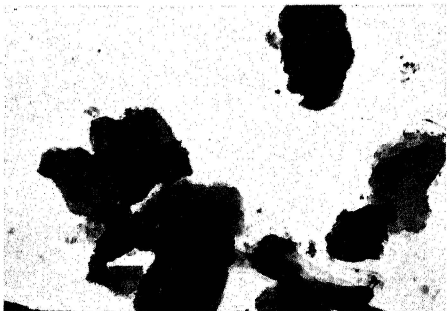
Fig. 26.—Residual diabase soil. Depth 9-16″.
Fraction 2μ-0.5μ.

Fig. 27.—Residual diabase soil. Depth 16-21″.
Fraction 2μ-0.5μ.

clay. Figure 29 (21-25″) presents a crystal of the fibrous secondary hornblende. Because of the instability of this mineral it could not persist with so much surface exposed in the more highly weathered surface horizons. No minerals of this character were observed in the A or B horizons. Figure 30 (21-25″) shows another crystal of secondary hornblende and in addition several micaceous clay minerals. The electron diffraction phenomena observed in the crystal above the micron mark is very characteristic of micas studied. Figure 32 (33-47″) reveals a fibrous type of clay mineral in the lower horizons of the profile. The structures exhibited are similar to the Mg-bentonites studied (22). The higher hydration and other surface properties of the clay of the lower horizons of the profile may thus be interpreted.

The Mg-clays were not observed in the more highly weathered horizons, probably because of their fibrous structures and instability. The large quantities of Mg released on the weathering of the ferro-magnesian minerals may explain its inclusion in the synthesis of the clay. Figure 33 (47-60″) represents one of the micas, possibly secondary, that exists in the weathering parent material.

$<0.5\mu$ Fraction: Figure 34 (0-5″) illustrates the dominance of the larger sized particles. The mechanical movement of the finer clay particles to the lower horizons in the profile is apparent by the characteristic absence of the normal distribution of particle size. Figure 35 (0-5″) shows an unusually large proportion of the finer clay in the surface soil. The clay particles are essentially thin plates. The absence of straight edged, sharp angled, hexagonal crystals eliminates a kaolinitic type of clay. Structures exhibited characterize the clay as essentially beidellite. Figures 36 and 37 (5-9″) display the micaceous cleavage of the clay minerals and differences in penetration of the beam of electrons show an overlap of plates. Figure 38 (9-16″) shows a higher proportion of the finer particles accumulating in the B horizon. The doubly terminated crystal in Figure 40 (16-21″) is characteristic of the structure of zircon or tourmaline. The appearance of an increasing percentage of opaque minerals in Figure 41 (21-25″) may be explained by the presence of a larger proportion of unweathered primary minerals. Figures 41 and 42 (21-25″) show an occasional crystal of halloysite, but the micaceous clay minerals constitute 95% of the fraction. Figure 43 (21-25″) displays the products of weathering from one of the primary minerals. The frayed edges of the particle and the similarity of surrounding products suggest their origin. Figure 44 (33-47″) shows the same fibrous Mg-clay existing in the finer fractions. The plate shaped clay minerals still maintain their dominance at this depth, but similar structures to those pictured are common. The clay immediately above the decomposing rock still shows the large proportion of the finer sized particles. The particles in Figures

Electron Micrographs of Clay From
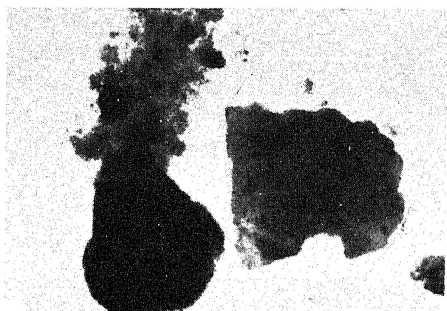
Residual Diabase Soil

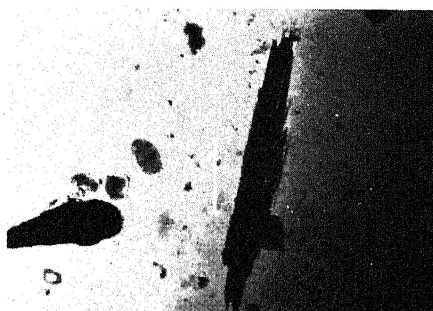Fig. 28.—Residual diabase soil.   Depth 16-21″.
Fraction 2μ-0.5μ.

Fig. 29.—Residual diabase soil.   Depth 21-25″.
Fraction 2μ-0.5μ.

Fig. 30.—Residual diabase soil.   Depth 21-25″.
Fraction 2μ-0.5μ.

Fig. 31.—Residual diabase soil.   Depth 21-25″.
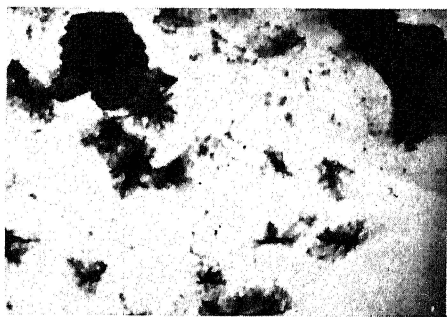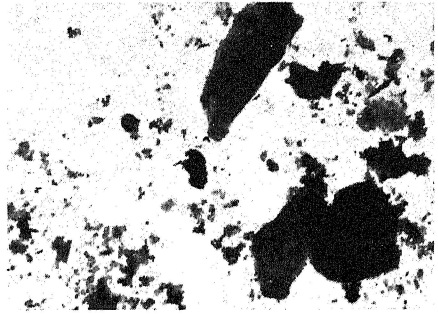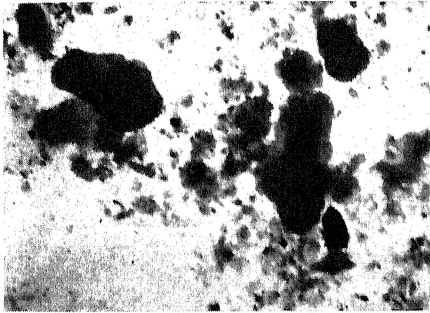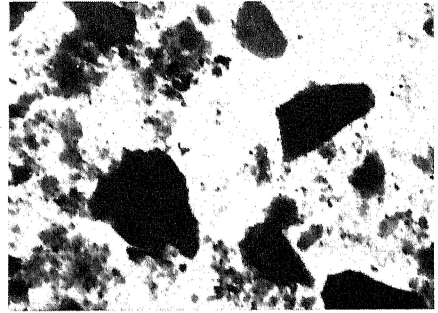Fraction 2μ-0.5μ.

Fig. 32.—Residual diabase soil.   Depth 33-47″.
Fraction 2μ-0.5μ.

Fig. 33.—Residual diabase soil.   Depth 47-60″.
Fraction 2μ-0.5μ.

Electron Micrographs of Clay From
Residual Diabase Soil
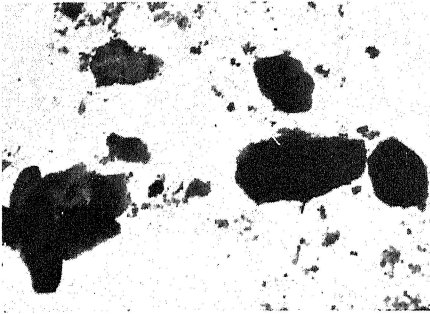
Fig. 34.—Residual diabase soil.   Depth 0-5″.
Fraction < 0.5 μ.

Fig. 35.—Residual diabase soil.   Depth 0-5″.
Fraction < 0.5 μ.

Fig. 36.—Residual diabase soil.   Depth 5-9″.
Fraction < 0.5 μ.

Fig. 37.—Residual diabase soil.   Depth 5-9″.
Fraction < 0.5 μ.
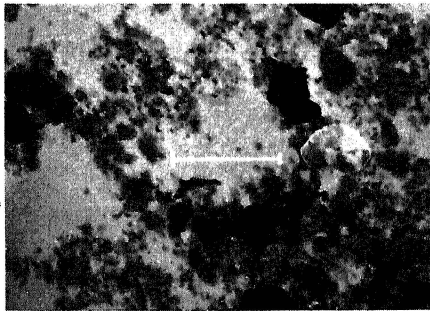
Fig. 38.—Residual diabase soil.   Depth 9-16″.
Fraction < 0.5 μ.
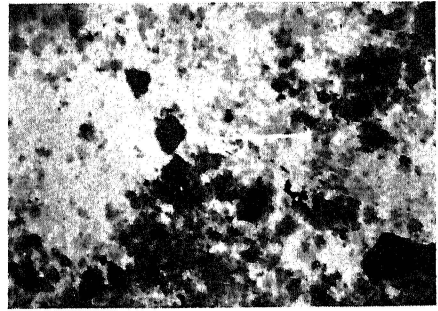
Fig. 39.—Residual diabase soil.   Depth 16-21″.
Fraction < 0.5 μ.

Electron Micrographs of Clay From

Residual Diabase Soil
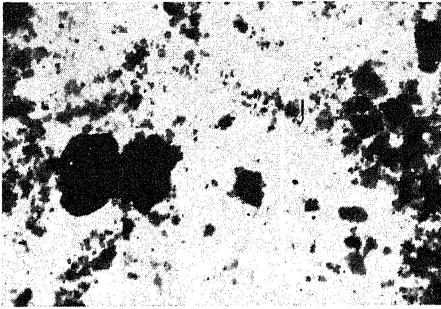
Fig. 40.—Residual diabase soil.   Depth 16-21".
Fraction $< 0.5\mu$.
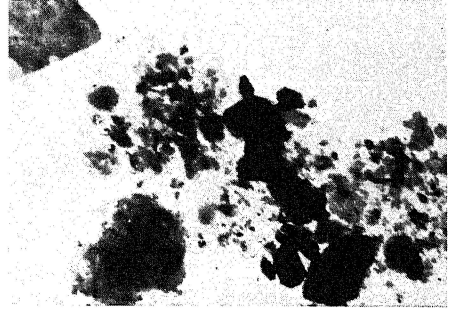
Fig. 41.—Residual diabase soil.   Depth 21-25".
Fraction $< 0.5\mu$.
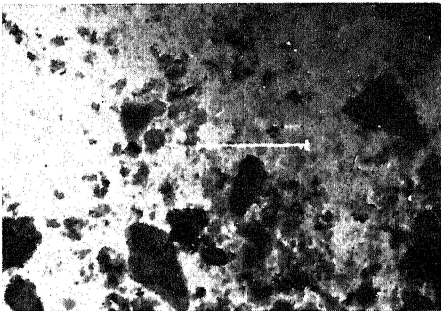

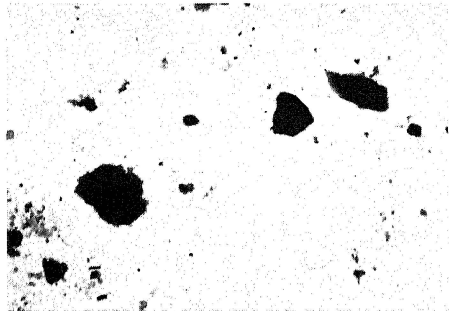Fig. 42.—Residual diabase soil.   Depth 21-25".
Fraction $< 0.5\mu$.

Fig. 43.—Residual diabase soil.   Depth 21-25".
Fraction $< 0.5\mu$.

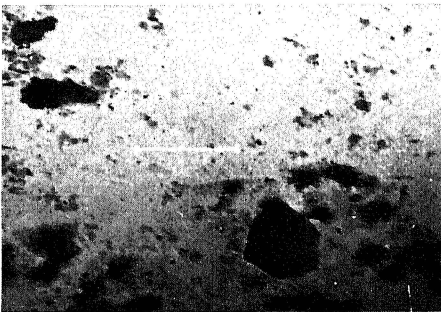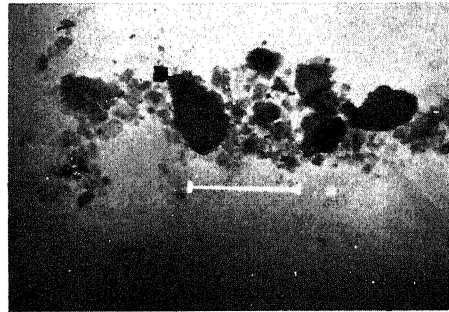Fig. 44.—Residual diabase soil.   Depth 33-47".
Fraction $< 0.5\mu$.

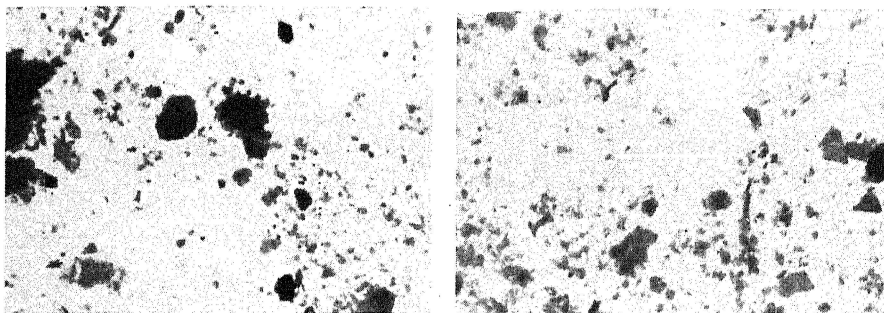Fig. 45.—Residual diabase soil.   Depth 33-47".
Fraction $< 0.5\mu$.

Fig. 46.—Residual diabase soil. Depth 33-47″. Fraction < 0.5µ.

Fig. 47.—Residual diabase soil. Depth 47-60″. Fraction < 0.5µ.

46 and 47 (47-60″) are plate-shaped and display similar structures to the clay throughout the profile.

The clay on the basis of structures exposed is essentially beidellite with numerous micaceous crystals. Small quantities of halloysite are present. The higher hydration and base exchange properties of the clay in the lower horizons may be adequately explained on the basis of the presence of fibrous magnesium clays at these depths.

CHEMICAL ANALYSES

The mineralogical studies were supplemented with chemical analyses of the horizons of the profiles. The analyses include determinations of (a) total exchange capacity, (b) total exchangeable bases, (c) exchangeable Ca, (d) exchangeable Mg, (e) exchangeable K and Na, (f) pH, and (g) total carbon. In addition, Table 25 gives typical complete analyses of the parent rocks as quoted by Erasmus Haworth.

TABLE 23. CHEMICAL ANALYSES OF THE RESIDUAL GRANITE SOIL

Sample Number	Depth in Inches	Total Exchange Capacity m.e./100gms.	Total Exchangeable Bases m.e./100gms.	Ca m.e./ 100gms.	Mg m.e./ 100gms.	Na & K m.e./ 100gms.	Total C pct.	pH	Total Exchange Capacity<2µclay m.e./100gms
1	0-4	7.47	4.66	2.30	1.24	1.12	1.304	5.4	60.1
2	4-10	7.89	3.55	1.02	1.92	.41	.613	4.6	50.9
3	10-18	16.15	5.23	.39	4.81	.03	.356	4.4	59.6
4	18-24	17.69	5.90	.25	5.32	.33	.275	4.3	59.3
5	24-30	12.37	5.02	.30	4.08	.64	.256	4.3	53.3
6*	26	13.38	4.73	.29	3.84	.60	.228	4.4	54.0
7	24-30	3.10	3.00	.45	1.20	1.35	.096	5.3	55.6
8	26	2.03	2.64	.90	1.10	.64	.072	7.1	84.6

* 5. Decomposed hull of weathered parent material
  6. Partially decomposed hull enclosing unaltered granite
  7. Crushed fragments of weathered parent material
  8. Crushed fragments of unaltered granite

Experimental Procedure

The ammonium acetate leachate method was used for determinations of total exchange capacity and the exchangeable cations. The calcium was precipitated as calcium oxalate and titrated with $KMnO_4$. Magnesium determinations were obtained by precipitation and ignition to $Mg_2P_2O_7$. The quantities of potassium and sodium were obtained by subtracting the summation of calcium and magnesium from the exchangeable cations. pH values were obtained with a Beckman pH electrometer. In the carbon analysis, two gram samples of air dry soil were ignited in a combustion furnace and the carbon dioxide collected in an ascarite bulb. All chemical determinations were made in duplicate. The results of the analyses are given in Tables 24 and 25.

TABLE 24. CHEMICAL ANALYSES OF THE RESIDUAL DIABASE SOIL

Sample Number	Depth in Inches	Total Exchange Capacity m.e./100gms.	Total Exchangeable Bases m.e./100gms.	Exchangeable			pH	Total Exchange Capacity <2μ clay m.e./100gms.
				Ca m.e./100gms.	Mg m.e./100gms.	Na & K m.e./100gms.		
1	0-5	18.33	8.50	3.66	2.93	1.91	5.1	49.5
2	5-9	12.99	8.57	3.61	3.49	1.47	4.8	57.0
3	9-16	18.12	11.81	4.98	5.82	1.01	4.9	58.7
4	16-21	18.47	17.68	8.74	8.31	0.63	5.1	49.6
5	21-25	18.93	20.01	9.29	9.07	1.65	5.2	48.7
6	25-33	26.64	29.77	14.58	14.72	0.47	5.5	46.1
7	33-47	36.75	37.71	18.74	18.01	0.96	5.6	44.7
8	47-60	33.23	25.84	14.93	8.28	2.63	6.0	53.9

TABLE 25. ANALYSES OF PARENT ROCKS (after Haworth)

	Granite Porphyry	Diabase
$Si O_2$	71.33	46.94
$Al_2 O_3$	12.55	16.91
$Fe_2 O_3$	3.75	12.53
$Fe O$	0.85	4.16
$Ti O_2$	0.55	--
$Mg O$	0.58	8.20
$Ca O$	0.94	9.00
$Na_2 O$	4.52	2.15
$K_2 O$	4.20	0.54
$P_2 O_5$	0.16	0.28
Ignition Loss	0.30	0.26

Residual Granite Soil

The total exchange capacity of the surface soil is low. These low values are associated with a low content of organic matter and clay. With the amounts of organic carbon so low, the effects of the clay content on the exchange capacity show up very well in the B horizon. The exchange capacities of the clay fraction substantiate the identity of the dominant clay mineral as beidellite. Since these values are in the lower limit for this group of clay minerals, support is given for the presence of smaller amounts of kaolinite. Slightly higher values of the exchange capacity of the lower horizons correlate very well with a higher percentage of $<0.5\mu$ clay, and emphasize again the value of surface exposed. The significant difference in the exchange capacity of the clay fraction from the unweathered parent material denotes that transition products of weathering possess different properties. The reduction in total exchange capacity of the unweathered and weathered parent material is explained by a corresponding decrease in the percentage of clay. A slight excess of the total exchangeable bases over the total exchange capacity in the unweathered rock indicates the presence of small quantities of soluble bases. This phenomenon is reflected again in the pH reading. A comparison of the exchangeable calcium in the parent material and the residual soil suggest rapid release of this cation. Increased quantities of calcium, sodium and potassium in the surface soil are the results of the effects of the vegetative cycle. The low potash content in the B horizon is associated with a root concentration at this depth. The relatively high amounts of exchangeable magnesium in the soil profile may afford an explanation for the movement of clay from the surface soil to the B horizon since Mg^{++} clays are fairly well dispersed in neutral or acid solution.

The acidity and the other indices given in Table 27, together with all mineralogical data, indicate an extremely poor soil from an agricultural standpoint. The balance of the exchangeable cations in the subsoil is entirely abnormal. It becomes all the more remarkable when the cation ratios in the original granite are considered. The very high ratio of magnesium to calcium in the exchange complex of the clay suggests that the clay was formed in an environment exceedingly low in calcium. The appearance of epidote with its immobilization of calcium helps us to understand how this may have happened. The epidote was probably formed before the clay.

Residual Diabase Soil

The high value of the total exchange capacity in the surface soil probably reflects the higher percentage of organic matter, the resultant of centuries of luxuriant vegetation. Similarity of chemical properties of the clay fraction eliminates the possibility of different

types of clay minerals in the A and B horizons of the two profiles. Studies with the electron microscope have shown the presence of fibrous magnesium clays in the lower horizons of the basic igneous profile. Their higher exchange properties may account for the higher values in total exchange capacity of the lower horizons of the untreated soil. Large quantities of exchangeable bases account for the vast differences in natural vegetation. The pH values are somewhat lower than would be expected from the exchangeable hydrogen present. More magnesium and other bases may have been rendered available by the chemical treatment of the soil, thus reducing the apparent amounts of exchangeable hydrogen. The similarity in the replacements of calcium and magnesium by hydrogen is illustrated by their relatively constant ratio from the parent material to the surface soil.

The similarity of the pH values of the various horizons of the two profiles suggest a profile development that is approaching maturity. Because of the extreme differences in the weathered parent material, wide variations would exist in an immature profile.

GENERAL DISCUSSION

The Factors of Rock Weathering

The changes which a compact igneous rock undergoes in its transition to an incoherent soil are determined by the nature and previous history of the rock itself and also by the new chemical environment to which it is subjected. In the light of recently acquired knowledge of mineral structures and their breakdown the following qualitative summary appears justified.

1. **Previous History.**—Many studies have been made of the complex changes which occur during the cooling and solidification of magmas. Two simple illustrations are here afforded by the thin section studies on the granite porphyry. Both concern the quartz crystals. In Fig. 5 we have an illustration of the attack upon quartz by later magmatic solutions leading to its partial solution. Of much greater importance in its effect upon the soil finally produced is the change from α quartz to β quartz. This occurred at about 570° C. during the cooling of the rock. It involved a 2% reduction in volume which caused the original crystals of α quartz to crack extensively in their transformation to β quartz. This has given the surface soil derived from the granite porphyry a size distribution curve dominated by the silt, whereas if the change had not occurred, the sand fractions would have remained in greater quantity. In general, presence of minute cracks and fissures in any rock enormously facilitates both physical and chemical weathering.

2. **The Changes in Chemical Environment.**—The course of chemical weathering is essentially a transition from a high chemical potential in the presence of the agents of weathering to a lower and

more stable value. Three associated agents of weathering operate simultaneously. They are (a) water, a liquid of small molecular size and high dipole moment, (b) dissolved carbonic acid which provides an acid medium of considerable buffer capacity and (c) dissolved oxygen.

3. **Mineralogical Constitution.**—In the make up of single minerals chemical and geometrical factors are closely interwoven and both play their part in weathering processes. Rocks, however, are seldom composed of single minerals, and there is no reason why the constituent minerals of rocks should weather independently of each other. The weathering of one mineral naturally alters the chemical environment of another. This aspect of the matter has, however, received practically no study from the physico-chemical point of view, although it is undoubtedly of great importance. Geologists have long recognized that certain secondary minerals arise from the simultaneous weathering of several primary minerals. The present study, for instance, illustrates the formation of secondary epidote from calcium feldspar and ferromagnesian minerals.

For the most part the weathering of igneous rocks consists in the decomposition of silicates. It is now possible to follow some of the chemical and structural factors involved.

The silicates in general are silicon-oxygen structures in which the part which the chemist would regard as the silicate radicle may take the following forms: discrete groups, linear chains, planar networks and three dimensional frameworks. In all cases the silicate or aluminosilicate radicle carries a negative charge which is balanced by the positive charges of cations. In accordance with this salt-like character the action of water can be regarded in the first instance as an interposition of H_2O dipoles between the cations and the silicate anions. The extent of this reaction is primarily conditioned by the degree of accessibility of the silicate or aluminosilicate radicle to water molecules. The geometry of the structure thus assumes great importance. Other things being equal, the more open the structure the easier the weathering. Channels smaller than the minimum diameter of water molecules will, however, be of secondary importance.

The degree of disruption caused by this tendency towards the interposition of water molecules will depend on the nature of the cation and on the way in which it is built into the structure. Both the valency and the coordination number of the cation are important factors, and the distribution of charge in the silicate radicle itself probably also plays a part. In the case of the zeolites and probably also that of the feldspars this first stage in weathering occurs with no disruption of the aluminosilicate structure.

That portion of the silicate into which water molecules have pene-

trated now has an opportunity to come to equilibrium with its environment. Thus under intense leaching by rainwater that ionic reaction most favored will be an exchange of the mobilized cations of the silicate for the small hydrogen ions from dissolved carbonic acid. Under less drastic conditions, however, metallic cations derived from the weathering of one mineral might interchange with those of another, provided the ionic sizes permitted. In more advanced stages of weathering the hydrogen ions may come from previously formed acid clays as demonstrated by Graham (7) or from organic acids derived from plant residues. In many cases this exchange of a metallic cation for the hydrogen ion causes the complete destruction of the original silicate lattice. At this stage, therefore, secondary minerals make their appearance. Numerous physicochemical studies of the weathering of the feldspars are in agreement with this general interpretation (3, 27).

In extreme cases differences in stability towards weathering agents are readily understood. For instance, we may compare orthoclase with kaolinite, whose structures are portrayed in a general way in Figures 48 and 49. In orthoclase the three dimensional silicate structure contains well defined channels containing the potassium atoms. These channels are just large enough to admit water molecules. Weathering will start at the outer surface and will proceed inwards by the successive replacement of potassium atoms by hydrogen. Kaolinite is constructed on a layer lattice plan, the charge on the silica sheet (Si_2O_3) being balanced by a hydrated double alumina sheet. As pointed out by Bragg (2) the high polarizability of the Al atom causes OH ions associated with it to become closely associated together. Thus instead of discrete groups neutralizing the negative charge of the silica layer we have a continuous double sheet of composition $(OH)_3 Al O_2OH$. Such a structure will present no points for attack by hydrogen ions except at the edges of the continuous sheets. Thus in spite of the ready basal cleavage which offers good accessibility to water molecules, kaolinite is an extremely resistent mineral to the agents of weathering.

The present investigation brings out clearly the great difference in rate of weathering between the potash feldspars and the calcium feldspars. This has frequently been the subject of quantitative investigation and has shown itself as a difference in rate rather than a difference in mechanism. As regards structural accessibility, the x-ray investigations summarized by Bragg (2) indicate only minor differences. The major difference is chemical rather than geometrical—the calcium feldspars carry a higher charge per unit of the aluminosilicate skeleton than the sodium or potassium feldspars. The exact way in which this affects the rate of weathering is not known.

Alongside the water molecules, dissolved oxygen also enters into accessible structures. In many minerals ferrous ions form part of the cationic establishment. In the presence of oxygen and water these are rapidly transformed to ferric ions. Such a change in valency completely upsets the normal balance of the silicate which is forced to take up one OH^- ion for each Fe^{++} oxidized to Fe^{+++}.
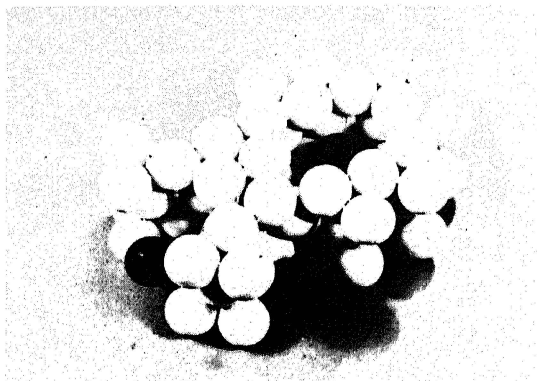

Fig. 48.—Atomic models of orthoclase. White spheres oxygen, black spheres potassium. Si and Al not shown.
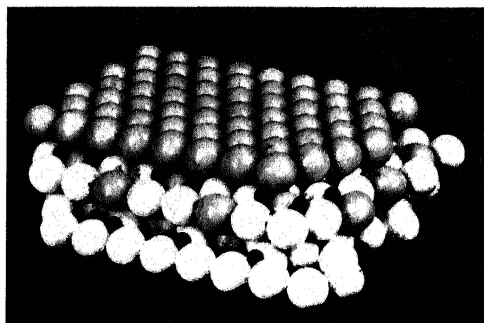

Fig. 49.—Atomic model of kaolinite. Larger spheres oxygen and hydroxyl. Smaller spheres Si and Al (enlarged somewhat).

In most cases this is geometrically impossible; hence the silicate decomposes completely and the OH^- ion is accommodated in the decomposition products. The presence of ferrous ions in a silicate structure thus causes very rapid breakdown once accessibility to the agents of weathering is established. Since this is a single stage process characterized by a very high electro-chemical potential it is not surprising that its consequences are the first to be recognized under the microscope. In the case of the pyroxenes and amphiboles the structural accessibility appears small, but the initial penetration by water molecules is facilitated by the numerous cracks along cleavage planes. Hence the oxidation proceeds rapidly and is easily recognized under the microscope in these cracks.

Profile Characteristics

The two igneous profiles here investigated show very strikingly certain similarities to the soils derived from secondary rocks under similar climatic conditions. In Missouri the latter lead neither to typical podsolization nor to laterization and the soil profiles which arise under these conditions show two characteristic features. In the first place the mechanical composition of the surface soil is dominated by the silt fraction and secondly the accumulation of clay in the subsoil is unaccompanied by chemical differentiation such as is found in the true podsols.

The dominance of the silt fractions (0.05-0.005 mm.) in the granitic soil can clearly be ascribed to the physical weathering of a cracked quartz grain and to the chemical breakdown of the feldspar, which still remains in particles of this size range even in the surface soil. The constancy of the total quartz percentage in all the layers below ten inches indicates that there is no appreciable enrichment by secondary quartz nor loss of quartz by chemical solution. The silty character of the surface soil is thus a consequence of the nature of the parent material rather than of the particular weathering conditions. In the diabase soil the silt fraction of the surface soil consists largely of secondary quartz and chalcedony which in a general way can be taken as reflecting both parent material and weathering conditions.

The marked enrichment of the subsoil in clay below ten inches depth is not accompanied by any notable change in the physical constants or the chemical properties in either profile. The clay fractions themselves are somewhat mixed in mineralogical character, but both appear to be dominated by clay of the beidellitic type. This is a very striking fact in view of the difference in chemical composition of the parent materials. The processes of weathering appear to be dominant in this connection, a conclusion which is strengthened by the observation that many Missouri soils developed from secondary materials under similar climatic conditions also show an accumulation of beidellitic clay in the subsoil.

The greater depth of the diabase profile as compared with the granitic profile enables us to separate some of the intermediate stages of the rock decomposition. Thus we find the maximum accumulation of mica at 33-47 inches together with a considerable accumulation of clay. At this stage the secondary silica is only small in amount. It increases steadily as the surface is approached. The clay fraction, although chiefly beidellitic, shows some variation with depth in the nature of the accompanying clay minerals. It is possible that the clay fractions would have shown much more striking variation both in mineralogical composition and in amount if there had been no movement downwards. Because of the readily

permeable character of this soil as shown by the volume weights, clay movement has proceeded to considerable depths. In the diabase profile there is so far no evidence of the formation of gibbsite $(Al(OH)_3)$ which commonly appears under lateritic weathering from basic igneous rocks (1, 8).

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