FACTORS AFFECTING CLAY FORMATION

by

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ABSTRACT

Barshad's method of calculating clay formation from the chemical analyses of the whole soil, the clay fraction, the nonclay fraction, and the mechanical analysis was applied to a large number of soils to determine the effect of climate, topography, parent material, vegetation and time on amount of clay formation. The amount of clay formed from 100 g of the nonclay fraction of the parent material was used as the yardstick for comparing clay formation in the different soils.

It was found that for a true evaluation of the effect of these factors on clay formation, it is necessary to determine clay formation in every horizon of a profile and that all soil profiles should be sectioned into horizons which are as nearly alike in thickness as possible. Maximum clay formation in a soil profile occurs in the horizon which is about 2–10 in. below the surface rather than at the immediate surface; as a rule, the amount of clay forming decreases below this maximum horizon. An increase in moisture and temperature enhances clay formation. The temperature factor mainly affects clay formation in the Great Soil Groups in the following order: Podzols < Gray Brown Podzols < Brown Earths < Chernozems < Prairies < Red and Yellow Earths (Latosols) < Laterites. Poor drainage enhances clay formation. Grass-type vegetation is more effective in clay formation than tree-type. Clay formation is greater from the finer grained and the more basic rocks. The more easily rocks fragment, the more clay is formed. The increase in age of a soil is believed to be expressed in the same manner as an increase in the intensity of clay formation, namely, as an increase in clay formation with depth and as an increase in the thickness of a soil profile. It was concluded that clay formation is relatively slow: clay forms at a rate ranging from 0.00001 g to 0.002 g of clay per year per 100 g parent material or from 0.6 to 120 lb of clay per acre foot of parent material per year.

INTRODUCTION

The study of clay formation in soils may be divided into three parts: (1) a quantitative evaluation of the amount of clay formed from a given amount of parent material, (2) a qualitative evaluation of the kind of minerals and other substances present in the clay fraction, and (3) an evaluation of the reactions and the agents involved in the formation of clay. Furthermore, an adequate understanding of clay formation requires a solution to all three problems in the context of the factors of soil formation: climate, parent material, organisms, topography, and time (Jenny, 1941).

The present paper deals with the first aspect of clay formation, namely, a quantitative evaluation of clay formation as it is affected by the factors of soil formation. However, before proceeding further it would be best to define the following terms which will be used in this paper: clay, clay formation, clay accumulation, and clay depletion. By "clay" is meant the whole inorganic fine fraction of a soil consisting of particles having a diameter of less than 2μ, 5μ or 1μ, depending on the analysis available. By "clay formation" is meant the conversion of particles greater than clay size to those of clay size regardless of the path and mechanism of formation. By "clay accumulation" is meant the gain of clay by a soil material other than by "clay formation", and by "clay depletion" is meant the loss of clay due to migration, cementation, or solution.

It is not possible to use the "clay content" of a soil as a measure of clay formation, because the clay content of a soil sample represents not only the clay formed but also the clay originally present in the parent material as well as the clay gained from an outside source by accumulation or the clay remaining after clay losses have occurred by depletion. It is therefore clear that the clay content of a given amount of soil from different soils may represent different amounts of parent materials; consequently, the relative clay content in such soils is not a direct measure of the relative intensity of clay formation. To obtain such a measure it is necessary to determine clay formation for all soils per unit volume of parent material having identical areal extent and identical depth functions because the agents causing clay formation operate on an areal basis and with a definite relation to depth. Methods for obtaining such measurements were developed recently (Barshad, 1955) but at present few data are available to which these methods may be applied. In the absence of data suitable for calculating clay formation on a volume basis, the best alternative is to calculate clay formation on a constant weight of the nonclay fraction of the parent material since this is the fraction from which the clay is formed. The present paper is a report of such an application.

The objective in making such calculations was to correlate the intensity of clay formation with the factors which operate in soil formation, namely, climate, parent material, topography, organisms, and time (Jenny, 1941).

Since the amount of clay in any given soil sample represents the net effect of the original clay content of the parent material, clay formation, and either clay accumulation or depletion, it is obvious that it would be impossible to evaluate clay formation in an isolated soil sample. It can be done only in the context of a soil profile—a three-dimensional section of a soil body from the surface to the parent material. In practice such a section is subdivided into several thin layers (horizons) and a soil sample from each layer is collected and studied separately. The subdivision of the profile into layers and the decision as to what layer is the parent material presents many problems. These problems and their solutions were discussed in a previous publication (Barshad, 1955).

Since the present paper is based on data for soils collected by various workers over a considerable length of time, the parent material for calculating clay formation is herein defined as the *nonclay fraction of the deepest soil horizon* of each profile studied, or the underlying rock if such was present.

The amount of clay formed is expressed in terms of grams of clay formed per 100 g of nonclay of parent material.

MATERIAL USED

The soils studied were chosen to represent a cross section of the Great Soil Groups as well as a number of soils within each group to illustrate the effect of variations in one or more of the soil-forming factors.

The original data for the soils used in the present study are presented in the original papers as listed in the references and in Table 1. No attempt was made in the present paper to rename the Great Soil Group by which the authors described their soils, even though in the terminology of present day pedology some of the Great Soil Groups are known by different names.

The method used to investigate the soils reported in the various papers included (1) field survey methods; (2) visual examination to describe the morphological features; (3) mechanical analysis to ascertain the textures; (4) total chemical analysis of the soils and of their separated clays; and (5) mineralogical methods, for a few soils, to determine their content of resistant mineral.

EXPERIMENTAL

To evaluate clay formation in a soil from its parent material two methods were developed: one based on mineralogical analysis and another on total chemical analyses of the soil and of the clay in the soil, and the amount of clay in the soil. These methods are described in detail in a previous publication (Barshad, 1955). In the present paper the majority of the results obtained are based on the second method. For the present discussion it need be stated only that the basic assumption underlying both methods is that the differences in the mineralogical composition or the chemical composition of the non-clay fraction of any soil from that of the parent material resulted from the formation of clay and other changes which may occur during soil development such as leaching of lime or gain in water of hydration and organic matter.

The results obtained in the present study are reported only in terms of number of grams of clay formed from 100 g of nonclay parent material.

The following factors affecting clay formation were considered: (1) relative position of the soil from the surface; (2) climate—the effect of temperature and rainfall; (3) effect of topography—mainly good drainage versus poor drainage as caused by the position of the soil in the landscape; (4) effect of vegetation—mainly grass versus tree vegetation; (5) effect of parent material; and (6) effect of time or the age of the soil.

To evaluate factors (1), (2), (3), (4) and (6), it is necessary to compare soils developed from similar or identical parent materials.

To compare clay formation among the different soils studied, it was found more helpful and informative to report the results graphically, as shown in Figs. 1 to 14, rather than in tabular form.

TABLE 1.—REFERENCES FOR SOILS USED IN THE PRESENT STUDY AS THEY APPEAR IN THE FIGURES

Figure No.	Soil Name	Reference
1	Becket	Marbut (1935), Anderson and Byers (1930).
	Chester	Brown and Byers (1938).
	Cecil	,, ,, ,, ,,
	Sheridan	Barshad (1955).
	Tzaneen	Van Der Merwe (1941).
2	Barkly East	,, ,, ,, ,,
	Settlers	,, ,, ,, ,,
3	Johannesburg	,, ,, ,, ,,
	Tzaneen	,, ,, ,, ,,
4	Neshoogte	,, ,, ,, ,,
	Jessievale	,, ,, ,, ,,
5	Mbabane	,, ,, ,, ,,
	Messina	,, ,, ,, ,,
6	Ermelo	,, ,, ,, ,,
	Louwsberg	,, ,, ,, ,,
7	Miami	Byers, Alexander and Holmes (1935). Holmes and Edginton (1930).
	Bethal	Mickelson (1942).
8	Bath Avon	Van Der Merwe (1941).
	Crecy	,, ,, ,, ,,
9	Miami	Marbut (1935), Holmes and Edginton (1930).
	Hasting	Brown, Rice, and Byers (1933).
10	Johannesburg	Van Der Merwe (1941).
	Krugersdorp	,, ,, ,, ,,
	Ermelo	,, ,, ,, ,,
11	Appling	Brown and Byers (1938).
	Cecil	,, ,, ,, ,,
	Davidson	Marbut (1935).
12	Manor	Brown and Byers (1938).
	Chester	,, ,, ,, ,,
13	Porter	Denison (1930).
	Durham	Denison (1930), Marbut (1935).
	Cecil	Marbut (1935).
14	Hartebeestpoort	Van Der Merwe (1941).
	Marikana	,, ,, ,, ,,
	Pilandsberg	,, ,, ,, ,,
	Marico	,, ,, ,, ,,

RESULTS

I. Effect of Relative Position of Soil from Surface on Clay Formation

The effect of the relative position of a soil from the surface on clay formation is shown by all the results presented in this paper. In all the soil profiles studied clay formation decreases with increase in distance from the surface. However, in the majority of the soil profiles the maximum of clay formation occurs not in the horizon immediately adjacent to the surface but in the one just below. This appears to be true whether clay formation is very high, as in the Red Earths, or very low as in the Podzols.

Because clay formation varies with depth, it is apparent that for the purpose of comparing clay formation among different soils it is of utmost importance that all soils should be sampled in identical manner, and that the profiles should be sectioned into relatively thin horizons ranging from 2 in. to 6 in.—depending on the total depth of weathering. Such a method of sampling has not yet been accepted by soil scientists, mainly because horizon differentiation as observed in the field is based on color, organic matter content, variation in clay content and structure, and other readily discernible differences. The horizons thus recognized, however, may not coincide with horizon differentiation as indicated by clay formation or other soil properties not readily discernible by field study. It is for this reason that soil profiles sampled for intensive study should be sectioned to yield a maximum number of points to enable proper comparison with other soils.

II. Effect of Climatic Variations on Clay Formation

It is well established that the categories of the Great Soil Groups are essentially an expression of soil development as a response to variation in climate as measured by differences in both precipitation and temperature. In the present report, methods for evaluating climate as a factor in soil formation will not be discussed. Such a discussion is found in Jenny (1941). The two climatic variables of importance are temperature and precipitation. The temperature factor regulates the " intensity " of inorganic reactions as formulated by Van Hoff's law and also affects the intensity of biological activity of the soil micro-organisms and plants. The mean annual temperature (Jenny, 1941) has been used as an index to designate or characterize the temperature of a locality with respect to soil formation. One of the more common indices to characterize rainfall effectiveness is Myer's N. S. Quotient (N.S.Q.) which is the mean annual rainfall in millimeters divided by the absolute saturation deficit. (See Figs. 2, 3, 4, 5 and 6.)

Among the Great Soil Groups two classes of soils exist, namely, the pedalfers and the pedocals (Marbut, 1935). The pedalfer soils are those which are subjected to sufficient rainfall to effect complete leaching of the profile as expressed by the absence of lime accumulation, whereas the pedocals are those in which there is insufficient leaching—expressed in the accumulation of lime somewhere in the profile.

The various pedalfer Great Soil Groups result chiefly from differences in temperature whereas those of the pedocals result chiefly from differences in rainfall. On the other hand, within each Great Soil Group differences still appear which are the result of differences in rainfall or temperature or both ; but these differences are still within the limits of that soil group.

For the present study soils belonging mostly to the pedalfer group were examined and therefore the differences found in clay formation may be attributed more to differences in temperature than in rainfall (Fig. 1).

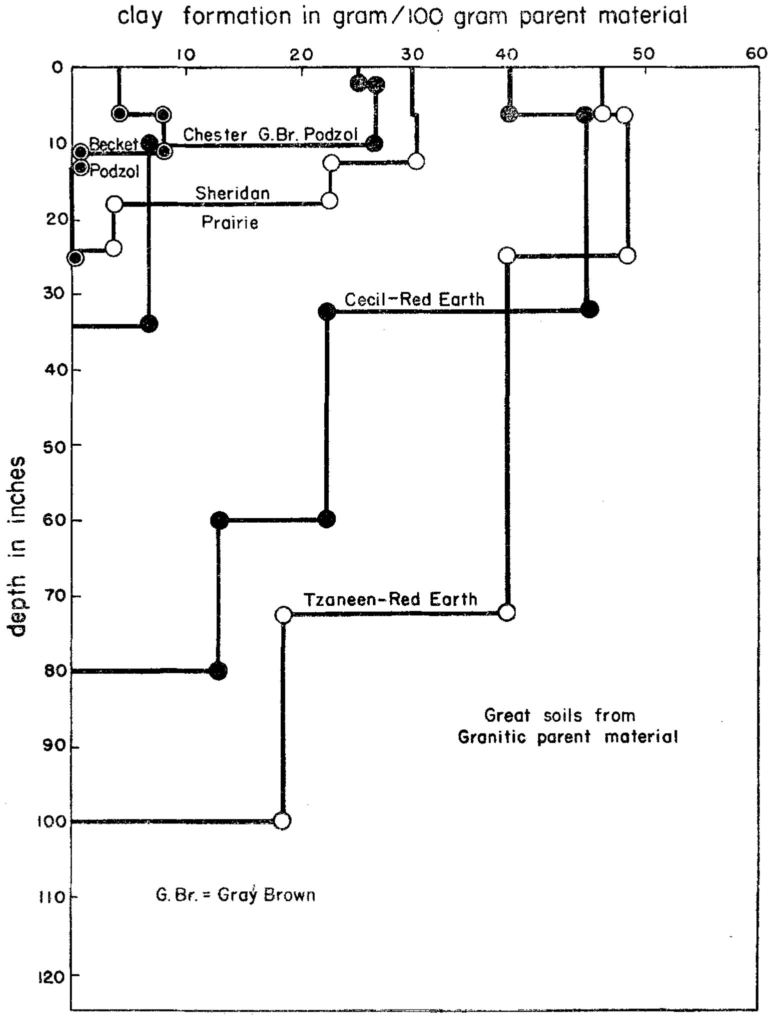


FIGURE 1.—Clay formation in several of the Great Soil Groups developed from granitic parent material.

Within some of the soil groups, differences in clay formation attributable to difference in rainfall or rainfall effectiveness as measured by the N.S.Q. values are also reported (Figs. 2, 3, 4, 5 and 6) The pedalfer Great Soil Groups studied are as follows : Podzols, Gray Brown Podzolic, Prairies, and Red and Yellow soils. The groups are arranged in order of increasing mean annual temperatures ranging from 43°F for the Podzols to 65°F for the Red and Yellow soils.

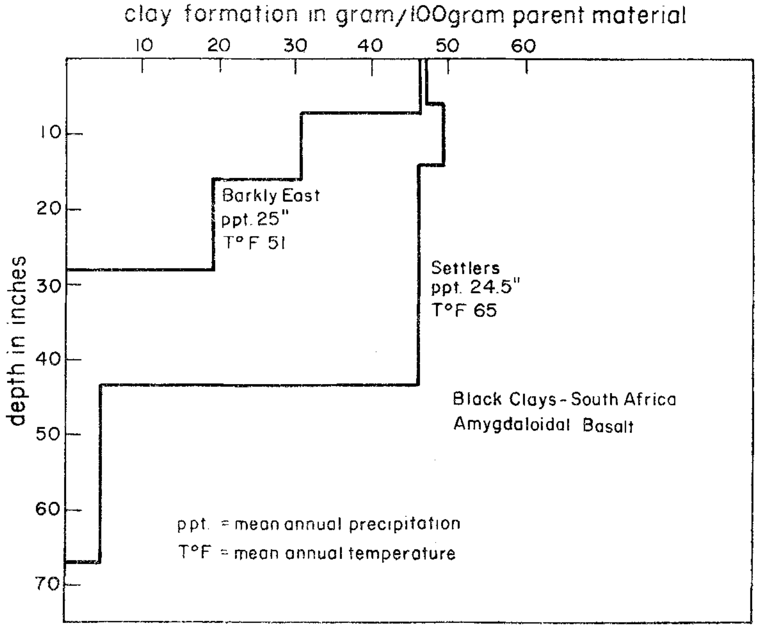


FIGURE 2.—Effect of temperature factor on clay formation as shown by Black Clay soils developed from amygdaloidal basalt.

Figure 1 summarizes the results for such a group of soils developed on granitic parent material and occurring in both the Eastern United States and the Union of South Africa. In the latter the results for the Red Earth only are included. These results clearly show that clay formation is at a minimum in the Podzols and at a maximum in the Red Earths. The difference is not only in the amount of clay formed at each horizon but in the increased depth to which the parent material weathers. In the Podzols and in the Gray Brown Podzolic soils, clay formation is confined to the surface 12–30 in., whereas in the Red Earths it persists to 10 ft or more from the surface. It is quite evident, therefore, that an increase in annual temperature favors greatly an increase in clay formation. Data for a Laterite soil on granite were not available, but it is well known that laterites represent the most intensely weathered soils. It is quite evident, therefore, that clay formation in relation to the Great Soil Groups may be arranged in the following increasing order: Podzols < Gray Brown Podzolic < Brown Earths < Prairies < Red and Yellow (Latosols) < Laterites.

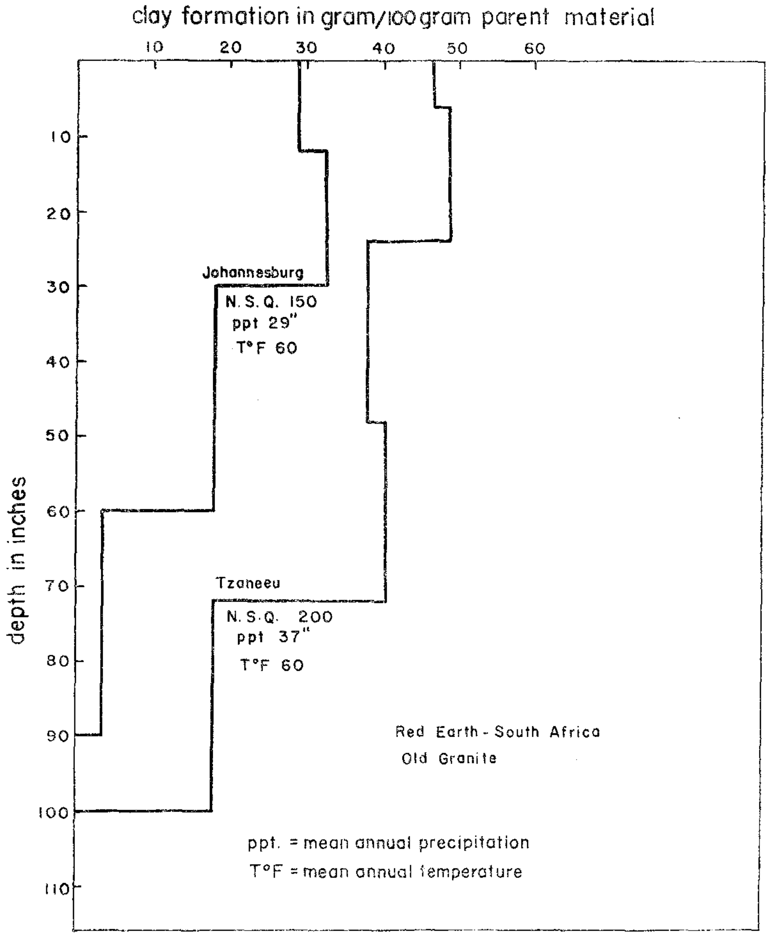


FIGURE 3.—Effect of precipitation factor on clay formation as shown by Red Earth developed from old granite.

The effect of an increased mean annual temperature on clay formation is also shown most strikingly in Fig. 2 which represents clay formation in two black clay soils from South Africa developed from amygdaloidal basalt. It is seen that the increased intensity of clay formation with increase in temperature is most sharply expressed in the lower horizons of the profile rather than in the surface horizon.

The effect of variation in rainfall at nearly equal temperatures is shown in Figs. 3 and 4 for Red and Yellow Earths on old granite in South Africa. It is seen that an increase in rainfall, measured either as precipitation or as Myers N.S.Q. values, brings about an increase in clay formation. Figure 5 shows similar results for soils from gneiss, and Fig. 6 for soils from dolcrite. Jenny (1941) using the clay content to a depth of 40 in. as a measure for clay formation has shown too that an increase in either temperature or rainfall, or both, brings about an increase in clay content.

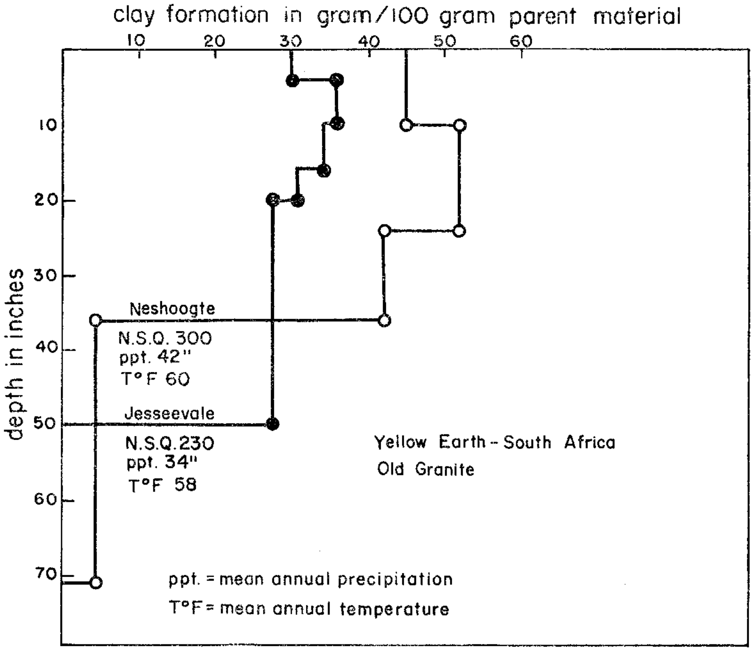


FIGURE 4.—Effect of precipitation factor on clay formation as shown by Yellow Earth developed from old granite.

III. *Effect of Topography*

One of the controlling conditions that topography imposes on soil formation is that of drainage, and, since drainage influences the moisture regime and the leaching conditions of a soil, it would be expected that clay formation would also be affected. Figure 7 illustrates such an effect in two soils in the United States belonging to the Gray Brown Podzolic group formed on almost identical calcareous till; namely, the Miami silt loam, with the better drainage conditions, and the Bethal silt loam, with poorer drainage. It is clearly seen that clay formation throughout the Bethal profile is higher than in the Miami, thus demonstrating that clay formation is enhanced by a decrease in drainage.

Another example leading to the same conclusion is illustrated in Fig. 8, which represents clay formation in two South African subtropical black clay soils developed from basalt.

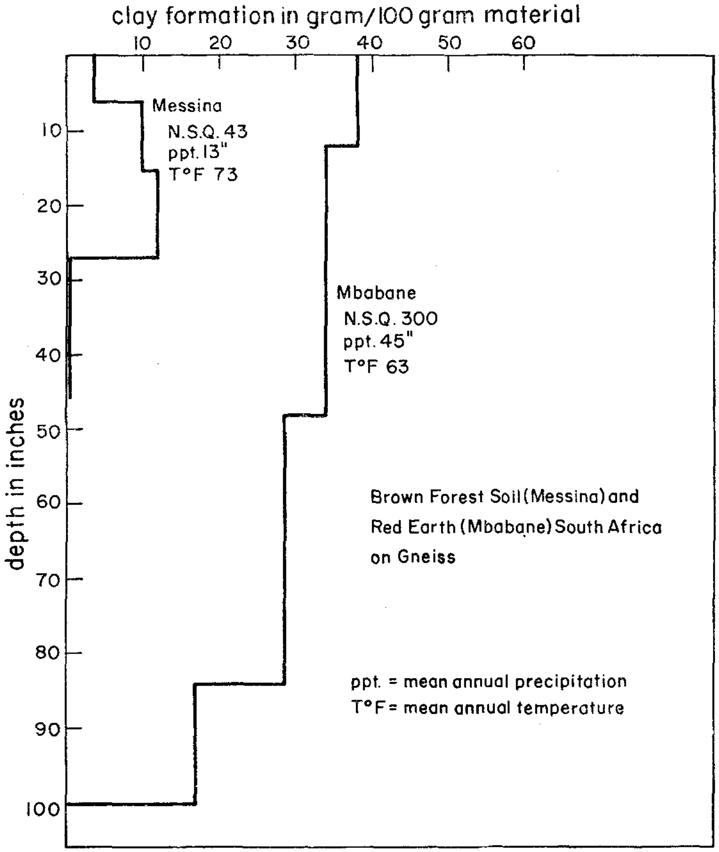


Figure 5.—Effect of the precipitation and temperature factors on clay formation as shown by soils developed from gneiss.

IV. *Effect of Vegetation on Clay Formation*

The effect on clay formation of tree-type vegetation versus grass-type vegetation may be discerned by comparing clay formation in two Great Soil Groups in the United States: the one under tree-type vegetation is represented by a Gray Brown Podzol—a Miami silt loam—and the other under grass-type vegetation is represented by a Chernozem—a Hasting silt loam. Both soils developed under similar annual temperatures and from very similar parent material: calcareous till and calcareous loess of equal texture. It is seen from Fig. 9 that clay formation is much higher in the Chernozem than in the Gray Brown Podzolic soil in spite of the fact that the latter is formed under conditions of greater rainfall. Since, as was shown, the higher rainfall should have favored the higher clay formation but did not, it is necessary to conclude that the grass-type vegetation is more effective in clay formation than the tree type.

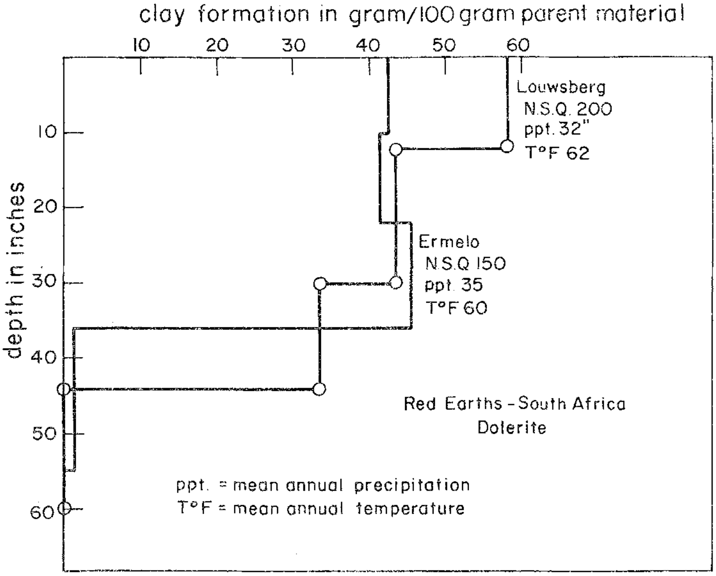


FIGURE 6.—Effect of the precipitation and temperature factors on clay formation as shown by soils developed from dolerite.

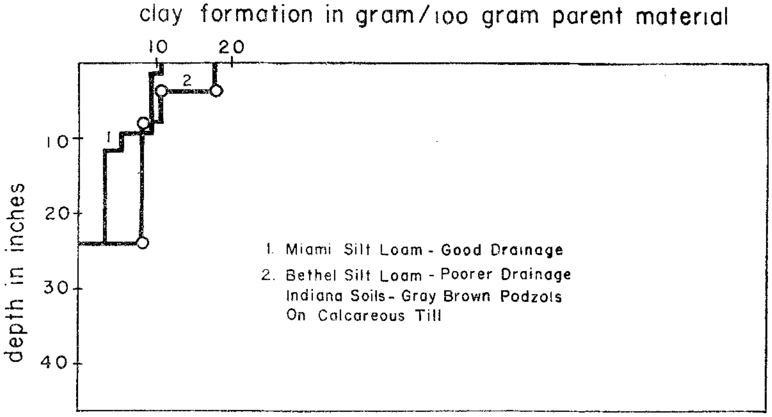


FIGURE 7.—Effect of drainage conditions, as determined by the topography factor, on clay formation as shown by soils developed from calcareous till.

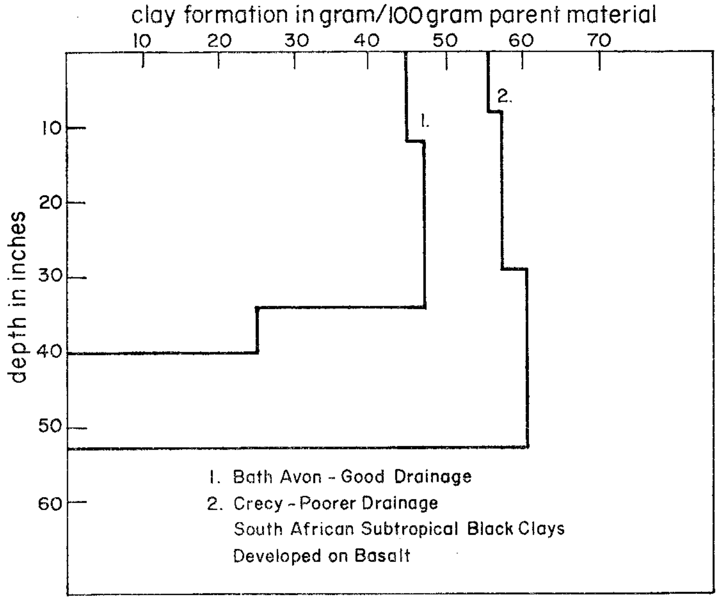


FIGURE 8.—Effect of drainage conditions, as determined by the topography factor, on clay formation as shown by soils developed from basalt.

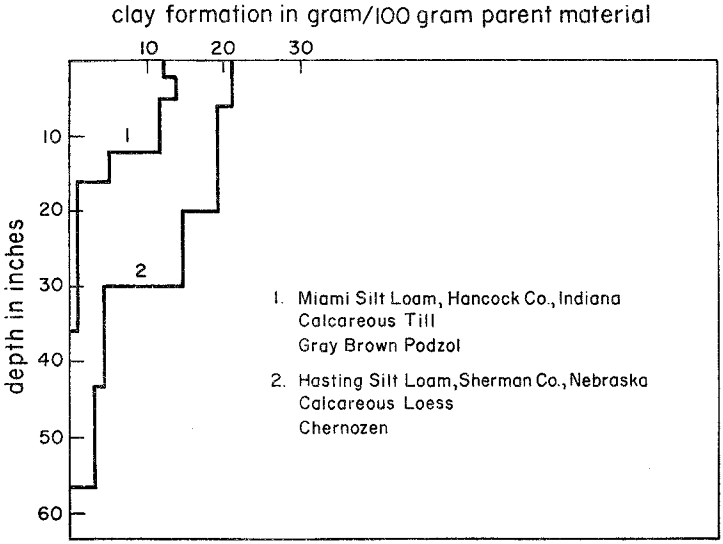
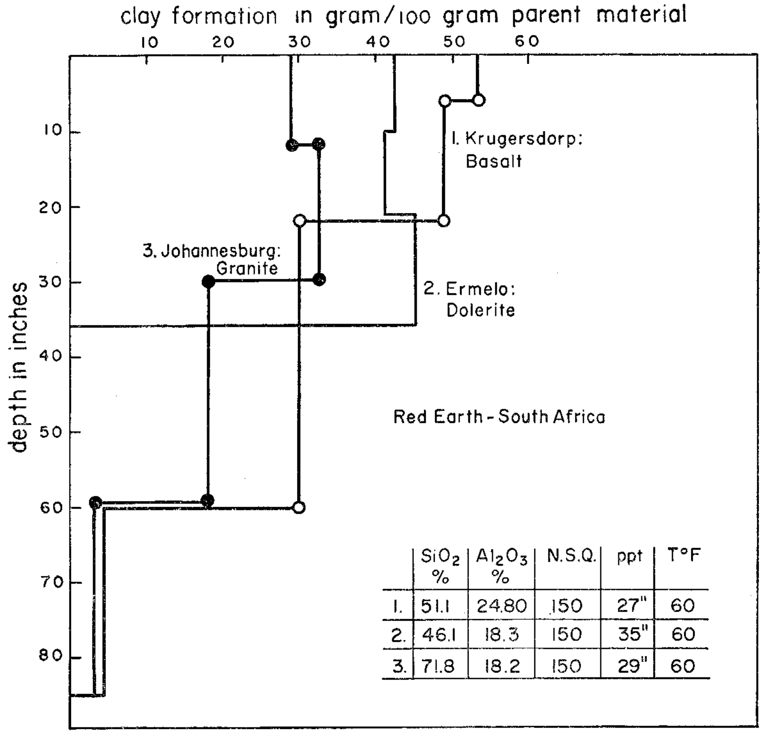


FIGURE 9.—Effect of vegetation factor on clay formation as shown by the Miami silt loam developed under a tree-type vegetation and the Hasting silt loam developed under a grass-type vegetation.

V. Effect of Parent Material on Clay Formation

In evaluating the effect of parent material on clay formation the following properties of the parent materials must be considered: (1) mineralogical composition, (2) texture of the minerals, (3) chemical composition, (4) porosity and density, (5) structure and fabric, and (6) degree of consolidation.

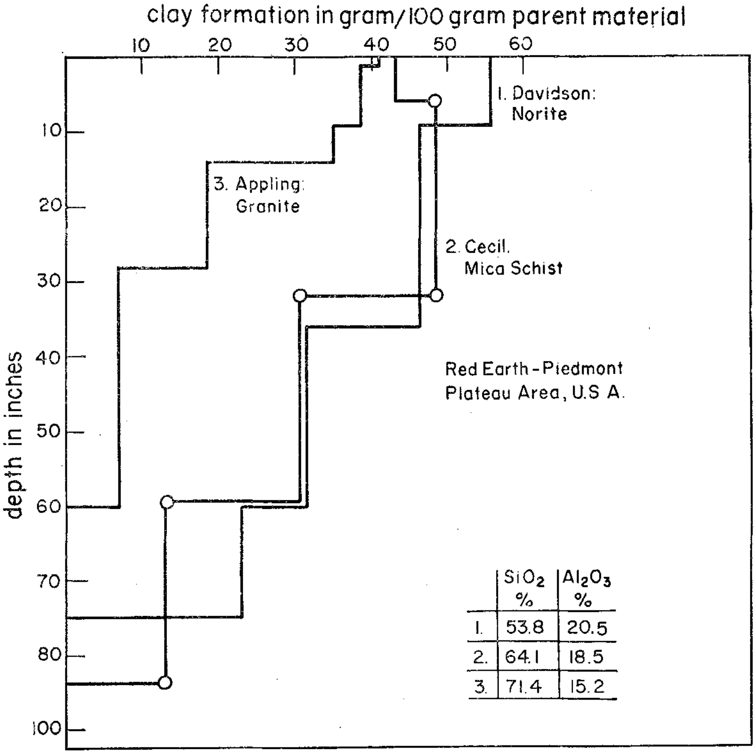


	SiO_2 %	Al_2O_3 %	N.S.Q.	ppt	T°F
1.	51.1	24.80	150	27"	60
2.	46.1	18.3	150	35"	60
3.	71.8	18.2	150	29"	60

FIGURE 10.—Effect of the parent material factor on clay formation as shown by the Red Earths of South Africa.

Whether the parent materials are igneous, metamorphic or sedimentary rocks is important only as far as these properties are affected. There are few places in which a great variety of parent materials representing systematic variation of the forementioned properties may be found and where the other factors of soil formation are identical. Fewer still are the studies of such soils. The most extensive contrast of the effect of parent material on clay formation may be found in soils formed on igneous rocks and on metamorphic igneous rocks, in two localities, namely in the Piedmont Plateau region of the United States and in the Union of South Africa where extensive studies on soil formation have been carried on for a long time.

Figure 10 represents clay formation on a basalt, a dolerite, and a granite which give rise to Red Earths (Latosols) in the Union of South Africa. Clay formation in the topmost two feet is highest on the basalt, least on the granite, and intermediate on the dolerite. The contrast between the dolerite and the basalt brings out the effect of texture of the minerals on clay formation since both rocks are basic and similar in mineralogical and chemical composition, but the dolerite being the coarser of the two. It is concluded that finer texture enhances clay formation. The contrast between the dolerite and the granite, on the other hand, brings out the effect of mineralogical and chemical composition on clay formation since both are of similar texture, but the dolerite being the more basic of the two. The higher clay formation from the dolerite leads to the conclusion that clay formation is enhanced by an increase in the base content. The contrast, therefore, between a granite and a basalt in clay formation reflects both texture and composition and as a rule it has been found in many localities that basalts yield more clay than granites. Among



	SiO_2 %	Al_2O_3 %
1.	53.8	20.5
2.	64.1	18.5
3.	71.4	15.2

FIGURE 11.—Effect of the parent material factor on clay formation as shown by the Red Earths of the Piedmont Plateau area, U.S.A.

the soils of the Piedmont Plateau, U.S.A., we also find evidence in support of the finding that increased basicity of rocks enhances clay formation as indicated by the Davidson soil from a norite in contrast to the Appling from a granite (Fig. 11). The effect of texture on clay formation is also indicated in this Figure by contrasting clay formation in a Cecil from a mica schist with that from a granite and from a norite. It is seen that although the mica schist is less basic than the norite and only slightly more basic than the granite, clay formation from the mica schist is nearly equal to that from the norite and is much greater than from the granite. These results again indicate that the fine grain of the mica schist enhanced clay formation.

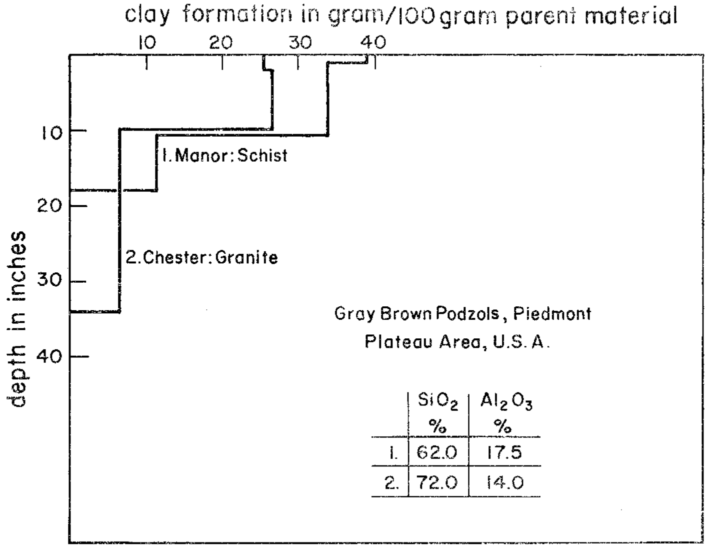
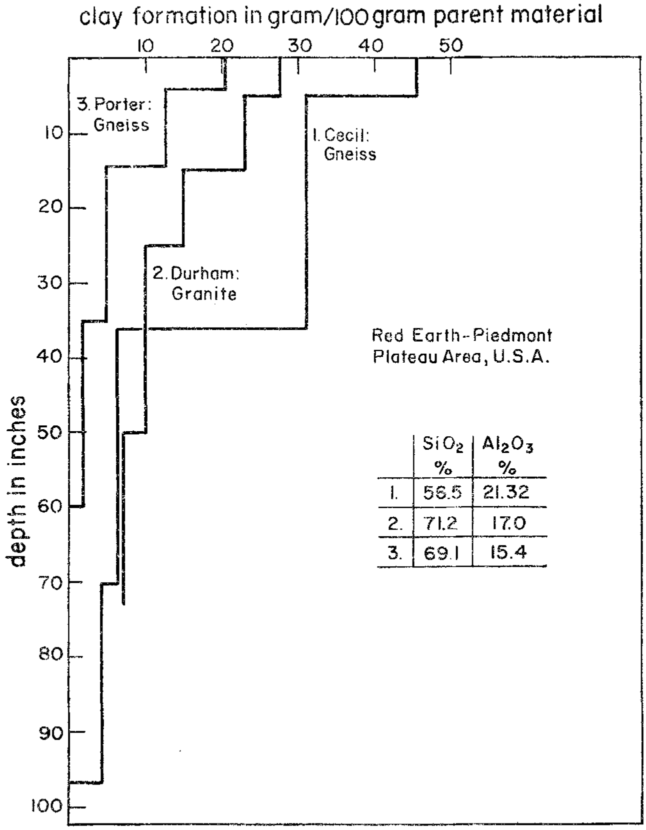


FIGURE 12.—Effect of the parent material factor on clay formation as shown by the Gray Brown Podzols of the Piedmont Plateau area, U.S.A.

Further evidence that clay formation is greater in soils developed from schists than from granite is seen in Fig. 12 representing clay formation in two Gray Brown Podzols from the Piedmont Plateau area of the U.S.A. The higher clay formation in the Manor, on the schist, than in the Chester, on the granite, is believed to reflect differences in both texture and chemical composition. The schist, with the finer texture and the higher base content, as reflected by the silica and alumina content, yields higher amounts of clay. In Fig. 13 there is a contrast of clay formation from a granite and two gneisses to illustrate further the effect of texture, structure, and chemical composition on clay formation. By comparing clay formation in the Porter and the Cecil, both derived from gneiss but the latter from a much more basic gneiss than the former, as shown by their silica and alumina content, it is again seen that clay formation is greatly increased by an increase in the base content of the rock. A comparison of clay formation in the Porter and the Durham, both developed from parent material of nearly equal chemical composition but different in texture and structure due to the one being a granite—the Durham—and the other a gneiss—the Porter—indicates that clay formation is greater from a granite than from a gneiss.



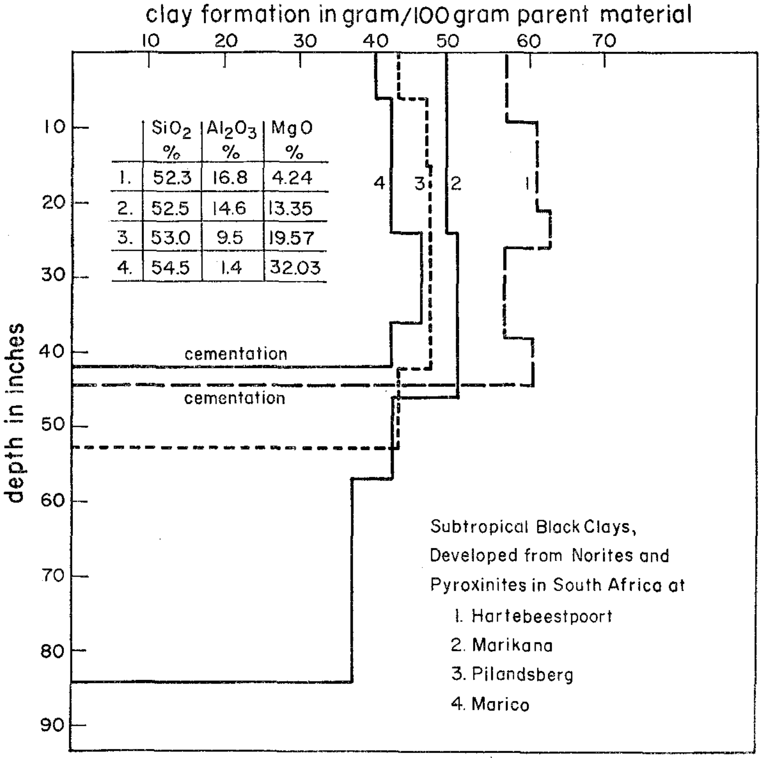
	SiO_2 %	Al_2O_3 %
1.	56.5	21.32
2.	71.2	17.0
3.	69.1	15.4

FIGURE 13.—Effect of the parent material factor on clay formation as shown by the Red Earths of the Piedmont Plateau area, U.S.A.

The effect of chemical composition on clay formation, particularly with respect to variation in Al_2O_3 and MgO content, is shown in Fig. 14 for a group of Subtropical Black Clay soils in South Africa developed from norites and pyroxinites. Clay formation is favored by larger amounts of Al_2O_3 and lower MgO content. It is also seen that clay formation remains high or increases with depth down to about four feet. In two of the profiles cementation occurs at four feet owing to lime accumulation.

VI. The Time Factor in Clay Formation

Several important questions may be raised regarding the effect of time on clay formation, namely: (1) What is the rate of clay formation within a given position in a soil profile? (2) Does this rate change with increased soil development? (3) What changes occur in clay formation within the profile as a whole with increase in time? (4) Does time have a qualitative effect as well as a quantitative effect on clay formation?



	SiO_2 %	Al_2O_3 %	MgO %
1.	52.3	16.8	4.24
2.	52.5	14.6	13.35
3.	53.0	9.5	19.57
4.	54.5	1.4	32.03

Figure 14.—Effect of the parent material factor on clay formation as shown by Subtropical Black Clays of South Africa.

Obviously, to determine the rate of clay formation it is necessary to know the age of the soil. Having this information one can determine an " average rate " of clay formation by dividing the " total clay formed " at each horizon from 100 g of parent material by the " age " of the soil. Such an " average rate," however, is strictly true only for the surface horizon since initially the

" total " profile did not exist. In fact the " growth " of the profile with depth, at least as measured by clay formation, depends on time and could be used as a criterion for measuring " relative " ages of soils if all the other soil forming factors had remained constant.

The change in rate of clay formation with time can be measured only if in a series of soils of known ages there is a great spread in age. In such a series of soils it should also be possible to answer the other questions as to the rate of growth of a soil with depth and as to the variation in rate of clay formation with depth. In fact in the absence of known ages of soils it is not possible to conclude whether the variation in clay formation with depth, as noted in the present paper, is due solely to the position of the parent material or to the length of time the parent material was subjected to weathering.

The effect of time on the qualitative aspects of clay formation may also be stated thus: does the kind of clay being formed change with increasing age of a soil?

At present none of these questions can be answered with certainty since a series of soils of known ages and of a sufficient spread in their ages are not known. Therefore, one can only attribute certain differences in soils to a possible difference in their ages and thus speculate as to the effect of time on clay formation.

To obtain a notion of the order of magnitude of the rate of clay formation in the absence of known ages of soils, two tables were constructed of hypothetical rates of clay formation based on the amounts of clay formed as shown by the calculations presented in this paper and by assuming various ages of soil formation. In Table 2 the rate is expressed as grams of clay per 100 g parent material per year and in Table 3 as pounds of clay per acre-foot for soils 50,000 years old and for a total clay formed ranging from 5 to 50 g per 100 g parent material. Even the higher rates of clay formation are low and range between 1 and 2 mg of clay per year per 100 g or between about 6 and 120 lb of clay per acre per year.

TABLE 2.—AVERAGE ANNUAL RATES OF CLAY FORMATION
(GRAMS OF CLAY FORMED PER 100 GRAM PARENT MATERIAL)

	Total Clay Formed					
	5	10	20	30	40	50
Total Number of Years	Annual Clay Formation					
25,000	0.0002	0.0004	0.0008	0.0012	0.0016	0.002
50,000	0.0001	0.0002	0.0004	0.0006	0.0008	0.001
75,000	0.000067	0.000133	0.000266	0.000399	0.000533	0.000666
100,000	0.00005	0.0001	0.0002	0.0003	0.0004	0.0005
200,000	0.000025	0.00005	0.0001	0.00015	0.0002	0.00025
300,000	0.0000167	0.0000334	0.0000668	0.0001	0.0001334	0.0001668
500,000	0.00001	0.00002	0.00004	0.00006	0.00008	0.0001

TABLE 3.—AVERAGE ANNUAL RATES OF CLAY FORMATION FOR SOILS 50,000 YEARS OLD FROM PARENT MATERIAL HAVING A BULK DENSITY OF 1.80 G PER CUBIC CENTIMETER

Total Clay Formed in 50,000 Years	5	10	20	30	40	50
	Grams of clay per 100 g parent material					
Pounds per Acre Foot per Year	5.97	11.90	23.80	35.70	47.65	59.60
Kilograms per Acre Foot per Year	2.230	4.446	8.892	13.338	17.789	22.23

The significance of such low annual rates of clay formation may be appreciated when compared with the total annual uptake of mineral nutrient by plants. One such illustration is shown in Table 4 taken from Liebing (1852). If only a small proportion of the ash content of plants is converted to colloidal constituents upon their decay in the soil, as it must happen under natural conditions, these constituents would be an important contribution to clay formation, at least to several important constituents of the clay fraction such as free SiO_2, Fe_2O_3 and Al_2O_3.

TABLE 4.—MINERAL CONSTITUENTS TAKEN UP BY VARIOUS CROPS DURING A FIVE-YEAR ROTATION (LIEBIG, 1852, P. 235)

	Pounds per Acre							
	Total Ash	H_2PO_4	H_2SO_4	Cl	CaO	MgO	K_2O + Na_2O	SiO_2
1st Planting :								
Potatoes	133.4	15.0	9.5	3.6	2.4	7.3	68.7	7.5
2nd and 4th Years :								
Wheat grain	59.5	27.9	0.6	0.0	1.7	9.5	17.5	0.9
Wheat straw	422.0	13.0	4.3	2.6	35.9	21.2	40.2	285.6
3rd Year :								
Clover	335.6	21.1	8.3	8.8	82.5	21.1	91.0	17.8
5th Year :								
Oat grain	49.9	6.9	0.4	0.2	1.7	3.6	5.9	24.5
Oat straw	70.7	2.1	2.9	3.2	5.8	1.9	20.4	28.3
Turnips	58.8	3.6	6.4	1.7	6.4	2.5	22.3	3.8
Total	1129.9	89.6	32.4	20.1	136.4	67.1	266.0	368.4

Because of the physical and chemical changes that occur within a soil during its development, undoubtedly both the rate of clay formation and the nature of the clay formed must also change with increasing age of a soil.

One of the most important effects of time upon clay formation is believed to be an increase in clay formation with depth from the surface. Such an increase is similar to the increase in clay formation brought about by an increase in temperature or precipitation. In other words, as the soil gets older it grows in depth. This feature of soil development is obscured to some extent by natural erosion which lends the impression that the thickness of a profile tends to remain constant. The greater thickness of the soil profiles in the tropical and subtropical regions and in the zone of the Red and Yellow Earth of U.S.A. and the Union of South Africa and elsewhere is believed to be due partly to their older age, aside from the higher temperature and rainfall under which they occur.

DISCUSSION

The significance of the variation of clay formation in a soil profile with depth may be appreciated when compared with the variations of clay content with depth. Whereas the former generally decreases with depth, except for a slight increase in the horizon just below the surface, the latter remains constant, increases to a maximum and then decreases, or decreases at a smaller rate than the decrease in clay formation. Such a difference between clay formation and clay content with depth clearly indicates that some of the clay that was formed in the surface horizons must have moved downward to the subsoil horizons. These results, therefore, are direct evidence in support of the theory of illuviation and eluviation in pedology which explains soil profile formation. These results, however, do not indicate whether the clay particles moved downward as such or whether their constituents moved downward and later combined in the lower horizons to form the clay. Evidence exists to indicate that both mechanisms may occur : The presence of " clay skins " and " oriented " clay aggregates in the subsoil is evidence in support of clay movement as discrete clay particles. On the other hand the presence in the subsoil of " clay " as pseudomorphs of silt and sand particles, as shown by x-ray, differential thermal analysis, and chemical analysis, indicates that the constituents of the clay have moved downward in solution and reacted with coarse-grained minerals to alter them to a clay crystal structure without reduction to clay size particle dimensions. Such pseudomorphs commonly occur in the lower parts of soil profiles formed from basic igneous rocks. By the method of calculating clay formation the presence of such " coarse clay particles " is indicated as " cementation "; that is, instead of a positive value for clay formation one obtains a negative value.

The occurrence of the maximum clay formation in many of the profiles studied in the horizon a few inches below the surface rather than in the immediate surface clearly indicates that the maximum chemical activity must also occur in this zone. This is due perhaps to the fact that this zone is subject to less dehydration and to less fluctuation in diurnal temperatures than the immediate surface and at the same time is subjected to the enhanced chemical activity caused by decomposition of the large amounts of organic matter in these horizons. It is also interesting to point out that for many plant species the maximum root activity (Weaver, 1926) is also centered in the horizon just below the surface rather than in the immediate surface. This suggests a definite relation between clay formation and root activity. Such a relation is not surprising, since root activity involves liberation of large quantities of CO_2 and absorption of the inorganic nutrients both of which are conducive to the maintenance of high chemical activity as measured by the decomposition of the nonclay fraction of the soil.

The absence in some profiles of a zone of maximum clay formation a few inches below the surface of the soil might indicate either that the surface few inches were eroded away or that the surface was disturbed by plowing or by earthworm and rodent activity.

One of the important applications that results from calculating clay formation for the whole profile is the possibility of drawing up a complete balance sheet for the transformation of a rock to a soil profile (Barshad, 1955).

The decrease in clay formation below the maximum zone may be explained either on the basis of a decrease in the intensity of chemical activity with depth or by the decrease in " age " of the soil horizon with increasing depth particularly in soils formed from solid rocks. However, both of these factors probably contribute to the decrease in clay formation with depth.

The increase in clay formation with increase in temperatures is not surprising in view of Van Hoff's temperature rule, which states: " For every 10°C rise in temperature the velocity of a chemical reaction increases by a factor of two to three " (Jenny, 1941). This rule affects not only the reactions occurring within the soil itself, but also above it, namely, plant growth. Plant growth in turn affects greatly clay formation directly through absorption of inorganic nutrients and release of CO_2 into the soil, and indirectly by the return to the soil, after death, of the inorganic constituents and the organic matter formed during growth. It is believed that these returned constituents play a very important role in clay formation (Basilevitch, 1955; Kovda, 1956).

Since most of the chemical reactions, including plant growth, cannot occur without water, it is not surprising that clay formation is higher the greater the effective moisture content of a soil. It is for this reason too that clay formation was found to be higher in the poorer drained soils, for poorer drainage enhances the effective moisture content of a soil.

The increase in clay formation due to any factor, such as temperature, moisture or time, is most pronounced not so much in the surface horizons but in the subsoil horizons. This is expressed as a relatively larger increase in clay formation with depth with the increased intensity factors or time of formation, and the resulting profiles show larger differences in the subsoils than in the surface horizons.

To understand the effect of vegetation on clay formation the following factors should be considered: the amount of growth, the relative amount of woody tissue vs. leafy tissue and their composition, the nature of the root system and the proportion of root to tops, and the composition and amount of the inorganic minerals absorbed by the plants and returned later to the soil upon the death of the plants. At present few data are available to evaluate each of these factors separately. However, the results presented earlier which showed that in clay formation grass-type vegetation is more effective than tree-type vegetation indicate that (1) a leafy-type vegetation is more effective than a woody type, (2) a fine root system is more effective than a woody type, (3) a vegetation which upon death is more thoroughly incorporated into the soil is more effective than one deposited on the surface in the form of leaf and woody litter, and (4) a vegetation high in mineral content, i.e. ash, is more effective than one low in ash content.

The greater clay formation found in rocks of finer texture is not surprising, since it is well known that reactions involved in the alteration and breakdown of minerals are primarily surface reactions. Therefore the finer minerals with the larger surface area break down or alter faster than the coarser ones and result in higher clay formation.

One of the main reasons for greater clay formation from the more basic rocks is that a larger proportion of the rock is subject to alteration owing to the higher content of basic minerals which alter to clay and the absence of quartz which resists breakdown. Since the clay minerals are mostly aluminosilicates, it is expected that the basic rocks having higher content of aluminosilicate minerals would yield more clay than rocks having a higher content of ferromagnesian minerals; such was found to be the case in the South African profiles from norites and pyroxinites (Fig. 14).

In contrasting clay formation from a gneiss, a granite, and a mica schist of approximately the same chemical and mineralogical composition, it was found that the amount of clay formed was least from the gneiss, most from the mica schist, and intermediate from the granite. It is believed that this difference is due to the ease with which these rocks fragment and fracture (causing increased surface area) during the early stages of weathering; fracturing occurring most readily in the schist, less in the granite, and least in the gneiss.

Factors which affect the " weathering " of minerals, such as chemical composition, crystal structure, isomorphous substitution in relation to crystal structure, and particle size were discussed in a previous paper (Barshad, 1955). All these factors are related to the intensity of clay formation. All the factors that enhance weathering also accelerate clay formation.

A comparison of " probable " rates of clay formation with annual absorption of mineral nutrient by plants suggests that at least part of the clay fraction is formed from these nutrients upon the death and decomposition of the plants in which these nutrients were present.

The realization that clay is formed extremely slowly suggests a variety of mechanisms for the kinetics involved in its formation. One of these, suggested previously (Barshad, 1955), involves adsorption by already existing minerals of free oxides or hydroxides, as they become available in the course of weathering, and their interaction upon adsorption to form the clay minerals.

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