

RATE OF CLAY FORMATION AND MINERAL ALTERATION IN A 4000-YEAR-OLD VOLCANIC ASH SOIL ON ST. VINCENT, B.W.I.

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ABSTRACT. The surface of a large fan of pyroclastic deposits erupted about 4000 years ago has weathered to a clayey soil generally 6 feet thick. The weathered deposits were originally andesitic ash consisting largely of glass and the minerals anorthite, labradorite, hypersthene, augite, and olivine. Fine vitric ash has altered to halloysite·4H₂O, allophane, and hydrated ferric oxide. The vitric lapilli have decomposed to halloysite·4H₂O. Anorthite crystals are etched in the soil and frosted in the underlying ash. Many hypersthene and fewer augite and olivine crystals in the soil are etched. Labradorite, hornblende, and magnetite are unaltered.

The 4000-year-old soil represents an early stage in the formation of the Yellow Earth soils of St. Vincent, which may themselves be classified with the yellow-brown volcanic-ash soils of Japan. Halloysite·4H₂O has been redeposited in some late Pleistocene ash beds on St. Vincent to form dark brown, waxlike *braunlehm*. Whether or not the yellow-brown volcanic ash soils of St. Vincent represent an early stage in the formation of a lateritic red soil cannot be demonstrated.

Clayey soil formed from ash at an average rate of 1½-2 ft/1000 years on St. Vincent, and glass decomposed at a rate of about 15 gm/cm²/1000 years. The slight degree to which the unstable minerals anorthite, olivine, and the pyroxenes are altered contrasts sharply with the decomposition of the glass. Survey of the literature suggests that mineral grains have altered more rapidly in some podsoles of the temperate regions than in the volcanic-ash soils of St. Vincent. This contrast in weathering rate may perhaps be explained by the low pH of podsoles and chemical effect of the rapidly decomposing glass of the ash soils.

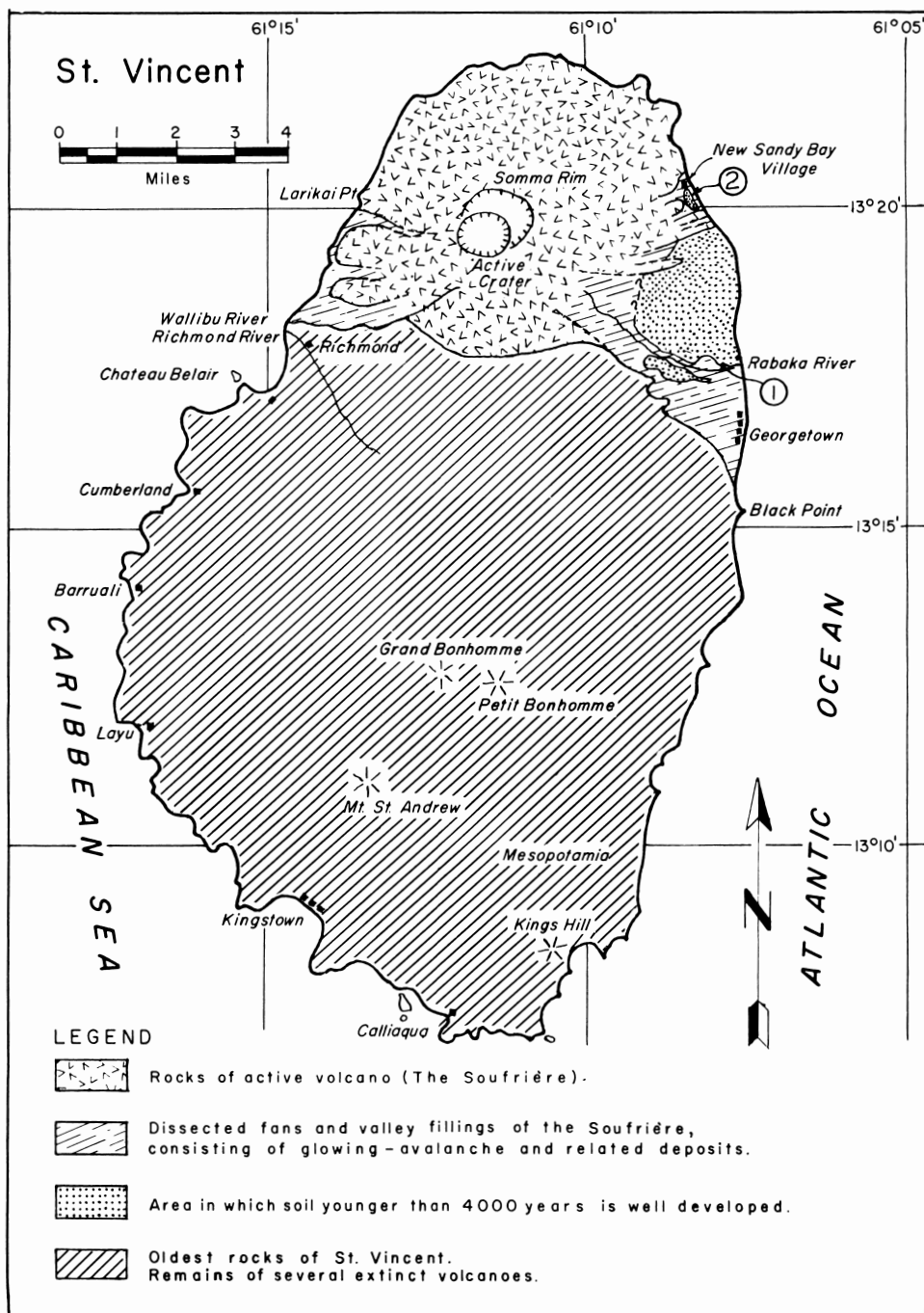
INTRODUCTION

Accurately dated soils are the necessary basis for determining the rate at which minerals are altered and clay is formed by weathering, yet such data are rare. The present study describes a soil developed on volcanic ash deposited about 4000 years ago. This soil provides a basis for estimating the rate at which the andesitic glass decomposed to clay and the anorthite, olivine, and pyroxenes were etched by hydrolysis. Early stages in the formation of halloysite·4H₂O are exhibited by weathered glass in the soil. Later stages in the weathering of similar andesitic ash can be observed in the late Pleistocene volcanic-ash soils of St. Vincent. Mineral alterations of the 4000-year-old soil are compared with those of other recent soils which can be dated reasonably well in order to compare the weathering rates of humid tropic and humid temperate climates.

GEOLOGICAL SETTING

The island of St. Vincent, which lies within the Windward Islands of the British West Indies, is 18 miles long and 11 miles wide. It comprises an active volcano, the Soufrière, and the remains of several extinct ones (fig. 1). After the Soufrière had reached its present size, intermittent vulcanian eruptions showered andesitic ash and lapilli over the island during the late Pleistocene.

Fig. 1. Map of St. Vincent showing principal geologic features and distribution of the 4000-year-old soil. Numbers (1) and (2) indicate localities where profile was sampled most extensively.



These deposits weathered during accumulation to produce a sequence of soils (Hay, 1959a). More recently, the Soufrière has discharged glowing avalanches of andesitic composition down the eastern and western sides of the volcano, deposited numerous massive ash deposits at its base (Hay, 1959b). The glowing avalanches of 1902 are the most recent of this eruptive phase.

Glowing-avalanche deposits, mud flows, and their stream-worked materials accumulated at the southeastern foot of the Soufrière to form a fan having a surface area of about 5 sq. mi. Charcoal from the deposit overlying the lowest of the exposed beds of the fan in the valley of Rabaka River gives an age of 4090 ± 50 years B.P., determined by Dr. E. S. Deevey of the Yale Geochronometric Laboratory (1958, personal communication). The base of the fan is not exposed here, but the deposit containing the charcoal was emplaced while the fan was relatively small. Unburned wood from the mud-flow portion of the upper deposit of the fan gives an age of 3890 ± 300 years B.P., according to Dr. H. R. Crane of the University of Michigan Memorial-Phoenix Project Laboratory (1958, personal communication). The fan had apparently reached its maximum size when the latter deposit was laid down. North of the fan pyroclastic deposits similar and probably equivalent to those of the fan have extended the shoreline seaward from wave-cut spurs. The seaward edge of the fan has been cut back by the waves, exposing the fan in sea cliffs 75 feet high. The coastal strip of ash deposits to the north has been eroded similarly, and its present form is that of a terrace. The massive deposits of the fan and terrace, including several feet of stratified ash above, have weathered to a clayey, yellowish-brown soil which is the object of the present report. One or more beds of fresh, unweathered ash and lapilli forming the surface layer of the fan were deposited by the eruptions of 1902-3 and possibly those of 1812 and 1784.

TOPOGRAPHY, CLIMATE AND VEGETATION

Most of the island of St. Vincent is rugged and mountainous, but the surface of the fan is rather smooth and slopes 5-6 degrees in a seaward direction. The climate is humid and tropical. Temperatures normally range between 68 and 87° F, and the mean is 80° F. The mean humidity is about 70 percent, although it may rise to almost 80 during the summer (Anderson, 1938). Annual rainfall ranges from less than 75 to more than 100 inches (Watson, et al., 1958) over the island. The annual average in Georgetown, on the southern part of the fan, is 90.3 inches, based upon unpublished records of the Ministry of Agriculture in Kingstown, St. Vincent. A rather well-defined dry season extends from December to May, while the period from June to January is relatively rainy (table 1). Most rain falls in heavy showers.

The fan is largely planted in coconuts and crops such as arrowroot and sugar cane; the coastal strip to the north is cultivated similarly. Semi-evergreen seasonal forest with undergrowth of vines and brush probably covered the fan during most of the 4000-year period of weathering, as this is the natural vegetation elsewhere on St. Vincent under similar climatic conditions (Watson, et al., 1958, p. 8-9).

TABLE 1

Average Monthly Rainfall for Georgetown, St. Vincent

[based upon 10 years' complete records and 3 years' incomplete records (unpublished) taken during the period 1931-1955 by the Ministry of Agriculture, St. Vincent.]

January	4.03 inches	July	9.97 inches
February	2.95 inches	August	9.23 inches
March	2.80 inches	September	11.82 inches
April	3.43 inches	October	13.56 inches
May	6.37 inches	November	12.46 inches
June	7.01 inches	December	<u>6.67</u> inches
		Total	90.30 inches

PROFILE OF WEATHERING

The complete soil profile over most of the fan and the terrace to the north includes half a foot to several feet of fresh ash and lapilli above 4 to 8 feet of clayey yellowish-brown volcanic-ash soil grading downward into fresh ash (fig. 2). The A horizon is represented by the surface layers of fresh ash, deposited by the eruptions of 1902-3 and possibly those of 1812 and 1784. The B horizon is represented by the yellowish-brown soil, and the underlying ash can be considered the C horizon. This terminology is not perfectly satisfactory, however, for the present A horizon was developed recently, and is not genetically related to the yellowish-brown soil. Individual massive ash deposits below the yellowish-brown soil range in thickness from 5 to 85 feet, averaging between 20 and 40 feet. Although these deposits appear unweathered, the finest ash is partly altered to clay, as will be shown subsequently, and many of the lapilli are slightly discolored by incipient alteration. Color of the dry soil is moderate yellowish-brown (10YR 5/4 in the Munsell system) or a shade intermediate between moderate yellowish-brown and dark yellowish-orange (10YR 6/6). The fresh-appearing ash below the soil ranges from light olive gray (5Y 6/1) to olive gray (5Y 4/1).

The yellowish-brown soil, which forms the principal chief object of this study, can be subdivided into an upper stratified unit 3-6 feet thick and a lower unbedded unit 1-3 feet thick. The lower unit is residual soil developed in place over the top of the massive ash deposits forming the fan and the terrace to the north. The upper unit is composed of evenly bedded ash layers weathered to a clayey soil. Beds of unweathered lapilli and coarse ash several inches thick are interbedded with the stratified soil but rarely form more than a tenth of this unit. Both upper and lower units of yellowish-brown soil appear weathered to the same extent, except for the beds of coarse ash and lapilli. Evidently either the processes of weathering altered the ash uniformly to a depth of 4-8 feet, or else the stratified ash accumulated slowly, and one layer of ash weathered before the next layer was deposited. The ash deposited in 1902-3 does not appear visibly altered.

The soil profile on the terrace locally differs from that of the fan. Where thickest, the upper part of this profile includes several feet of massive, yellow-

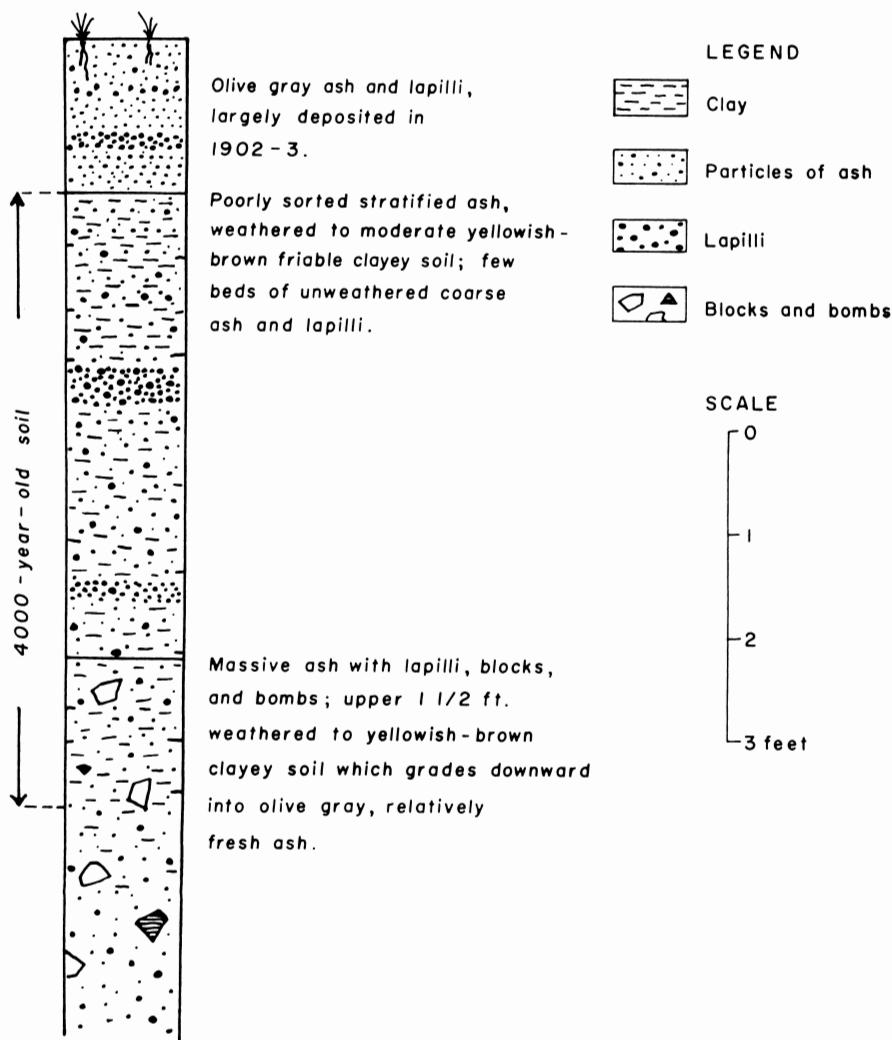


Fig. 2. Generalized profile through the 4000-year-old soil exposed along Rabaka River.

ish-brown soil containing a mixture of fresh and weathered lapilli, and cross-bedded laminae of sand rich in magnetite and pyroxene which may be the deposit of sheet or rill-wash. This part of the profile may contain redeposited (colluvial) soil and will be excluded from the following discussion. Crude potsherds are locally common 2-3 feet below the top of the profile, within or near the base of the colluvial material.

The fan and the terrace to the north were formed no more than 4140 years and no less than 3590 years ago, judging from the C^{14} dates of 4090 ± 50 and 3890 ± 300 years B.P. obtained for deposits of the fan. The yellowish-brown

soil apparently represents the interval of time between formation of the fan and the present (at least 3590 years and no more than 4140 years) and will be referred to as the 4000-year-old soil of St. Vincent.

TEXTURE OF ASH DEPOSITS

The massive ash deposits, source of the lower unit of yellowish-brown soil, are poorly sorted, unconsolidated mixtures of fine, flourlike, to coarse ash containing 15 to 30 percent of lapilli, blocks, and bombs. Blocks and bombs form as much as 40 or 50 percent of a few deposits, which can be termed breccias. Mechanical analysis of the ash fraction of a typical deposit is given in figure 3. The residual soil developed on the massive deposits contains a higher proportion of fine material than does the fresher ash below. As an example, particles finer than 4 microns form 1-2 percent of the fresh ash and 10 percent of the weathered part of the same bed (fig. 3). In another profile through a massive ash deposit, particles less than 2 microns in diameter form 4-5 percent of the yellowish-brown soil, 2.5 percent of slightly clayey ash near the base of the soil, and 0.5-1 percent of the underlying ash. Crystals form a higher proportion of material in the 1/8-1 mm fraction of weathered ash than of the fresh ash, suggesting that much of the vitric ash 1/8 to 1 mm in diameter has

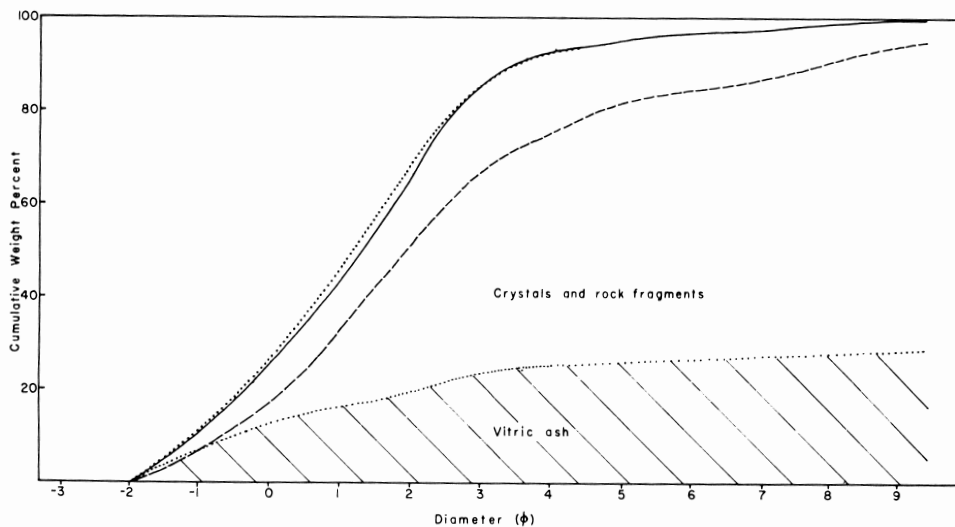


Fig. 3. Mechanical analyses of material finer than 4 mm in fresh and weathered portions of massive ash deposit roughly 4000 years old exposed near mouth of Rabaka River (fig. 1, loc. 1). Dashed line represents a sample of yellowish-brown soil from upper 4 inches of a 1-foot thickness of residual soil. Solid line represents sample of olive gray ash 6 feet below yellowish-brown soil. Dotted line is an analysis of the sand fraction of a sample from the glowing avalanche deposit discharged into the valley of Rabaka River in 1902, which is included for comparison. Cumulative percent of vitric ash in the 1902 deposit is indicated by diagonal shading. Original composition of the 4000-year-old ash deposit was similar to that of the 1902 deposit, judging from visual comparison of the sieved fractions. Material coarser than 4 mm forms between 15 and 30 percent of the samples above and was not included in cumulative curves. Ash 1/16-4 mm in diameter was sieved, and the finer material was analyzed with a hydrometer.

been reduced in particle size during weathering. Some of the fine material in the soil samples may, however, have been produced by comminuting coarse particles of decomposed ash in the disaggregation and dispersion of the soil for size analysis.

The beds of weathered ash forming the upper part of the profile vary from ash of coarse sand (1-2 mm) and granule (2-4 mm) size lacking a fine matrix to poorly sorted materials in which lapilli and coarse ash particles are embedded in a matrix of clay and medium to fine ash. These poorly-sorted beds are, however, somewhat better sorted than the residual soil developed on the massive ash deposits below. One sample analyzed contains about 3.5 percent of material finer than 2 microns.

Porosity and permeability are high in the beds of coarse ash lacking a fine matrix and in the unconsolidated olive gray ash below the soil. Porosity and permeability are fair to moderately good in the soil. The highly permeable beds of coarse ash interbedded within clayey, poorly sorted ash contain little if any clay washed from higher parts of the profile, suggesting that appreciable clay may not have been redeposited downward within the profile.

ORIGINAL COMPOSITION OF ASH

The ash deposits weathered to form the 4000-year-old soil were andesitic in composition and derived from the fragmentation of porphyritic scoria and pumice or equivalent liquid. Crystals form 60-80 percent, by weight, of ash 1/8 to 1 mm in diameter and a smaller proportion of both finer and coarser ash. Glass forms all of the remainder except for several percent of accessory fragments of older non-vesicular andesite. The fresh, unweathered glass is slightly to moderately microlitic and colorless to pale brown in thin section and has a refractive index between 1.535 and 1.550. The crystals include plagioclase, pyroxene (both hypersthene and augite), olivine, and magnetite in order of decreasing abundance. A few cleavage fragments of green hornblende were noted, but no apatite was found. The plagioclase includes both sodic labradorite (An_{50-60}) and anorthite (An_{90-100})¹. The bulk of plagioclase crystals less than half a millimeter across are labradorite, and most of the larger crystals are anorthite. Nearly all of the labradorite crystals are subhedral to euhedral and thinly coated with glass, but many of the anorthite crystals are cleavage fragments. Euhedral anorthite crystals are thinly mantled by sodic labradorite. Composition of the hypersthene is En_{67-72} and that of the olivine is Fo_{77-82} . N_z of the augite is 1.715-1.717. The bulk of pyroxene crystals are euhedral; the olivine occurs commonly as euhedral, rounded, or broken crystals. Juvenile lapilli consist of andesitic scoria² in most deposits and andesitic pumice in a few others. Phenocrysts constitute 25 to 50 percent, by weight, of the lapilli and are similar in composition to crystals of the ash.

MINERALOGIC CHANGES PRODUCED BY WEATHERING

The fine vitric ash in the soil has weathered to yellowish-brown clay, and

¹ Composition of plagioclase, hypersthene, and olivine is based upon refractive indices and curves of Tröger (1956).

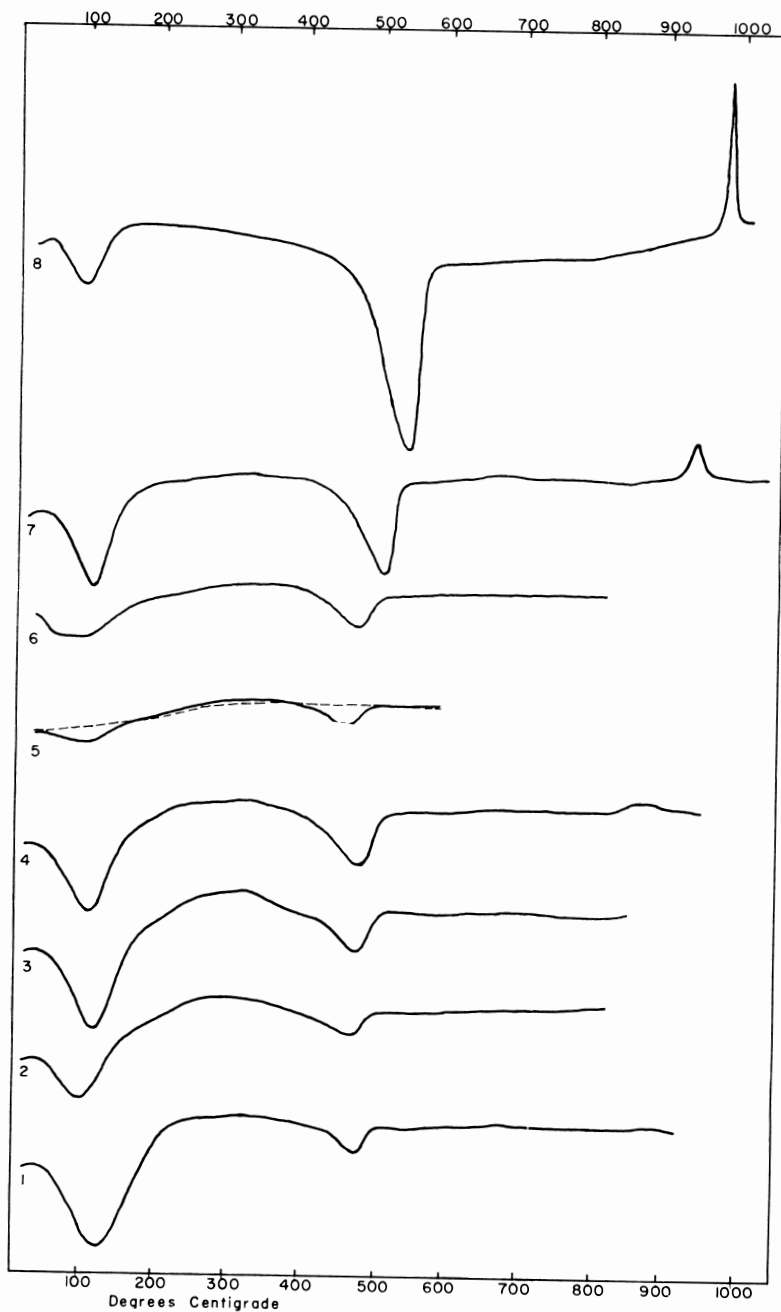
² Vesicular glass having a porosity greater than 65 percent is considered pumice and that with less than 65 percent is considered scoria.

most coarse particles of vitric ash and have been decomposed to yellowish-brown or cream-colored material, soft enough to be crushed between the fingers, but preserving the original vesicular texture. Although few scoria lapilli are entirely weathered, the margins of most are highly altered. Marginal zones of many vesicular lapilli in the olive gray, relatively fresh ash are slightly altered. The early stage in alteration of the glass is represented by fine, dust-like inclusions, a yellowish-brown color (in transmitted light) and a refractive index as much as 0.030 higher than that of the fresh glass.

Halloysite·4H₂O and allophane are the clay minerals formed from the decomposing glass. Most scoria and lapilli of vesicular glass have weathered to halloysite·4H₂O, and the fine ash has altered to a mixture of halloysite·4H₂O and allophane. The finest, fluorlike ash has altered to halloysite·4H₂O and allophane in even the fresh-appearing olive gray deposits exposed along Rabaka River, as much as 85 feet below the soil. X-ray diffractometer patterns give weak but unmistakable spacings of halloysite·4H₂O in fractions of the soil finer than 5 microns, 2 microns, and 1/2 micron (e.s.d.). The basal spacing of untreated samples prepared at room temperature is 9.8Å, which expands to 11.3Å with glycerol-solvation and decreases to a broad, poorly defined peak of 7.4-7.9Å in samples heated at 150° C for 2 hours. Differential-thermal curves (fig. 4) of decomposed lapilli are similar to those of halloysite·4H₂O, and those of the clay derived from fine ash are similar to curves produced by mixtures of halloysite·4H₂O and allophane (Sudo, 1954). The differential-thermal peaks of halloysite·4H₂O in the soil are much weaker than those of pure halloysite, however, and the higher-temperature D.T.A. peaks, at 470-490 and 870° C. compare with corresponding peaks at temperatures of 570 and 980° C, respectively, in a sample of halloysite (A.P.I. #12) from Bedford, Indiana. Both irregular, sponge-shaped masses (allophane?) and small rod-shaped crystals (halloysite) as well as larger angular to irregular particles (partly decomposed glass?) can be seen in electron micrographs of the fraction finer than 1 micron from one sample. Many of the irregular, sponge-shaped masses resemble those in the electron micrographs of allophane published by Birrell and Fieldes (1952). The yellowish-brown color of the clay is probably produced by hydrated ferric oxide from the decomposing glass.

Early stages in decomposition of the glass illustrated by this soil do not support Kanno's suggestion (1956) that glass decomposes directly to allophane, from which hydrated halloysite later crystallizes. The earliest stages of decomposition are exhibited by slightly and moderately decomposed lapilli, in which the endothermic D.T.A. peaks (fig. 4, nos. 5 and 6) are properly proportioned for halloysite·4H₂O. Allophane is most abundant in the clay fraction of samples from the most highly weathered part of the profile (fig. 4, nos. 1 and 3). The allophane, may, however, crystallize to halloysite·4H₂O, in later stages of weathering, for the most highly altered of the late Pleistocene ash deposits of St. Vincent, weathered for several tens of thousands of years, consist chiefly of halloysite·4H₂O and contain little if any allophane (Hay, 1959a).

Anorthite crystals in the soil are etched by weathering, but the labradorite is not visibly altered. Between 2 and 5 percent has probably been dissolved from anorthite crystals a millimeter across in the yellowish-brown soil, estimat-



ing from the depth and extent of solution pits. Anorthite crystals in the underlying olive gray ash are faintly frosted. Most hypersthene crystals are slightly

etched in about two thirds of the samples of soil which were examined. Etching is developed only on terminal faces and fractured surfaces roughly parallel to them and ranges from faint pitting to fine needle-like points parallel to the *c* axis (Hay, 1959, pl. 2B). Perhaps as much as a hundredth has been dissolved from hypersthene crystals a millimeter long. Terminal and less commonly the prismatic faces of augite crystals are slightly to moderately etched in one sample but are not visibly altered in the others. Many olivine crystals are faintly frosted to moderately pitted in most samples of the soil. As much as two or three percent of olivine may have been etched from some 1 mm crystals. A small number of the olivine crystals, both etched and unetched, are coated by a reddish-orange to brown iridescent surface tarnish. The latter crystals may have been tarnished before they were deposited, for a similar coating can be observed in some olivine crystals in samples of fresh ash. Etched olivine crystals have the same composition as unetched ones, and tarnished crystals the same composition as untarnished ones. Both large and small crystals of the same mineral are pitted to similar depths, but of course a larger proportion has been etched from the smaller crystals. Both feldspar and ferromagnesian phenocrysts in the decomposed pumice appear unaltered, and ferromagnesian crystals in the lower, olive gray part of the massive ash beds are unetched. The etching of the minerals described above resulted from hydrolysis rather than simple ionic solution. The reaction products—ions and possibly colloidal particles—were removed from the altering minerals by water percolating through the soil, thus etching the margins of the crystals.

CLASSIFICATION AND COMPARISON WITH OLDER VOLCANIC-ASH SOILS
OF ST. VINCENT

Weathered late Pleistocene ash deposits of andesitic composition (Hay, 1959a) illustrate further stages in the type of weathering described above. The bulk of these beds are yellowish-brown, indurated to friable massive soils and paleosols in which the glass is now represented by halloysite·4H₂O giving stronger and sharper x-ray patterns than that of the 4000-year-old soil. Both the exothermic D.T.A. peak and the higher of the two endothermic peaks fall between those of well-crystallized halloysite and corresponding peaks of the younger soil (fig. 4, no. 7). Allophane and gibbsite have not been detected in

Fig. 4. Differential-thermal curves of volcanic-ash soils of St. Vincent and halloysite from Bedford, Indiana. All curves except Bedford halloysite are based on the clay fraction finer than 2 microns (e.s.d.). Curve 1 represents yellowish-brown soil developed on a massive deposit of the 4000-year-old fan, and curve 2 represents a sample of fresh-appearing ash 7 feet below sample 1. Samples 1 and 2 collected from locality 1, fig. 1; mechanical analyses of samples are given in fig. 2. Curve 3 represents a sample from the middle of a 4-foot thickness of yellowish-brown clayey soil (fig. 1, loc. 2), and curve 4 represents a sample of unconsolidated, slightly clayey ash three feet below sample 3. Curve 5 represents scoria lapilli only slightly altered and includes base line of furnace (dashed line) to show relative size of endothermic peaks. Curve 6 represents decomposed pumice lapilli from sample of soil whose clay fraction is given by curve 3. Curve 7 represents halloysite·4H₂O from highly weathered late Pleistocene ash of St. Vincent. Curve 8 represents halloysite from Bedford, Indiana (A.P.I. Sample No. 12). Samples suspected of containing undecomposed glass (No's. 2, 3, 5 and 6) were not heated beyond 800° C because of the danger of fusing in sample-holder. Platinum-rhodium thermocouples were used and furnace was heated at a rate of 12½° C per minute.

these soils. Ferric oxide, most or all of which is hydrated, forms 10-15 percent of the clay fraction of weathered late Pleistocene ash analyzed by Hardy, et al. (1934, p. 12). Halloysite·4H₂O has been redeposited in the late Pleistocene beds most highly weathered to form dark brown, impermeable, waxy soil having a fabric similar in thin section to the European *braunlehm* described by Kubišna (1953, p. 266-273).

Anorthite is largely destroyed in the highly weathered (i.e. eastern-coastal) facies of late Pleistocene ash (Hay, 1959a). Most crystals are partly or wholly replaced by halloysite·4H₂O pseudomorphs, and others are represented by small etched remnants of fresh plagioclase within unfilled pseudomorphous cavities retaining the shape of the original crystals. Hypersthene and augite have been moderately to extensively etched in this facies of weathered ash. Much olivine is partly or wholly replaced by "iddingsite," but some crystals—particularly the more magnesian ones—are etched. Many crystals of olivine are represented by etched relicts of fresh olivine inside packets of iddingsite. Much labradorite is slightly to moderately etched or replaced by halloysite·4H₂O, but some is unaltered. Hornblende and magnetite are unaltered in most beds and slightly etched in a few.

Slightly later stages of weathered ash appear to be illustrated by a paleosol several feet thick developed on andesitic tuffs and Breccias underlying the late Pleistocene ash deposits of the eastern coast. Halloysite·4H₂O is more abundant than in the overlying ash, and minerals are more highly altered. This soil is moderate yellowish-brown to dark brown and friable to indurated. Some dried samples of the friable soil rapidly decrepitate when placed in water. The fabric generally resembles that of *braunlehm*.

The absence of gibbsite in these weathered ash deposits seems surprising in view of the humid tropic climate of St. Vincent and the advanced state of the weathering. Perhaps the silicic composition of the volcanic glass has determined the formation of halloysite·4H₂O, and the latter is not readily altered in the soil environment on St. Vincent. It should be emphasized that the soils described above are principally those of the coastal areas; few samples were collected from the higher, rainier part of the island.

The yellowish-brown volcanic-ash soils of St. Vincent have been formerly considered Yellow Earth soils (Hardy, et al., 1934 and Watson, et al., 1958), but they may perhaps be appropriately classified with the volcanic-ash soils of Japan, recently elevated by Kanno (1956) to the status of a major world soil group. The yellowish-brown volcanic-ash soils of St. Vincent closely resemble the yellow-brown sub-group of Japanese volcanic ash soils, which, like those of St. Vincent, were derived from pyroxene andesite ash (Kanno, 1956). The yellowish-brown volcanic-ash soils of St. Vincent were believed by Hardy, et al. (1934, p. 11) to represent an early stage in the formation of "lateritic" red soil (latosol). Whether or not this is true cannot be demonstrated by the evidence at hand.

AMOUNT AND RATE OF WEATHERING

Yellowish-brown clayey soil 4 to 8 feet thick has developed over a period of 3600-4000 years on St. Vincent, indicating an average rate of 1½-2 ft/

1000 years. Dacitic ash weathered on El Salvador, in a periodically dry savannah climate, at only a slightly lower rate than on St. Vincent, judging from Weyl's data (1954). Glass is decomposed to halloysite, and hypersthene is slightly etched in a soil locally a meter thick (Weyl, 1954, p. 59) developed on an ash layer deposited 2993 ± 360 years ago (Williams and Meyer-Abich, 1955, p. 23). Thus, the formation of a soil similar to that of St. Vincent has proceeded at an average rate of 1 foot/1000 years. By contrast, no mineral alterations were detected in soils 205, 566, and 1200 or more years old developed on volcanic mud-flow deposits near Mt. Shasta, California, under a humid temperate climate, and a clouding of glass pellicles enclosing mineral grains is the only observed evidence of clay formation (Dickson and Crocker, 1953 and 1954).

Where well developed, the 4000-year-old soil on St. Vincent originally contained about half a foot of glass, exclusive of pore space, which has decomposed to clay.³ Assuming a specific gravity of 2.6 for the glass, then approximately 40 gm of glass decomposed per sq cm over a period of roughly 4000 years, a rate of about 10 gm/cm²/1000 years. If the altered very fine ash of the massive olive gray deposits is included, the rate is increased to about 15 gm/cm²/1000 years. Clay formed from the glass does, however, include appreciable undecomposed glass as well as allophane and halloysite·4H₂O, judging from the small size of diffractometer D.T.A. peaks.

Hypothetical annual rates of clay formation have been estimated by Barshad (1958), assuming various ages of soil formation. These rates are expressed in grams of clay formed per year from 100 grams of parent material and range from 0.1 mg clay/100 gm parent material/year to 2.0 mg/100 gm/year. The weathering rate on St. Vincent is difficult to estimate in these terms, as the degree to which the glass has decomposed to clay over periods less than 4000 years is not known. If, however, the time required to decompose the glass to clay is assumed to be 4000 years (it may have been less), then the rate is 100 gm clay/100 gm glass/4000 years, or 25 mg/100 gm/year, a rate considerably higher than even the highest rate estimated by Barshad. The clay formed by weathering of the glass is not wholly allophane and halloysite, hence less than 100 grams of clay *minerals* were formed from 100 grams of glass. Assuming arbitrarily that the clay contains 60 percent of undecomposed glass, then the rate of clay-mineral formation is no less than 10 mg/100 gm/year.

The rate of clay formation inferred from the 4000-year-old soil is not the maximum attainable by weathering, even on St. Vincent. Andesitic late Pleistocene ash deposits of varied texture weathered at different rates on St. Vincent. Most rapidly weathered were the poorly sorted deposits consisting largely of fine vitric ash (the eastern coastal facies of Hay, 1959a). The 4000-year-old soil resembles texturally the late Pleistocene ash (western coastal facies) which weathered more slowly than the eastern coastal facies. Thus the fine vitric ash of the eastern coastal facies of late Pleistocene age probably decomposed to clay at a rate appreciably faster than 15 gm/cm²/1000 years.

³ Clay is used in a broad sense to include all decomposed vitric material, regardless of particle size.

The slight degree to which the unstable minerals anorthite, olivine, and the pyroxenes are altered in the 4000-year-old soil contrasts sharply with the relatively complete decomposition of the glass—a result to be expected from the chemical instability and high porosity of the glass. Weyl (1954) noted a similar contrast on El Salvador and furthermore stated that minerals in the volcanic-ash soils of El Salvador weathered even more slowly than did the feldspars and heavy minerals of postglacial weathering profiles in humid temperate climates.

Brief survey of the literature does indeed suggest that minerals have altered more rapidly in some podsoils of the temperate regions than in the volcanic-ash soils of El Salvador and St. Vincent. No reference was cited by Weyl in support of his statement, which may refer to his earlier studies in Germany (1951, 1952). Pyroxene and hornblende are almost wholly destroyed in the A horizon of some post-glacial podsoils he studied, although they are only slightly altered in brown-earth and gley soils of the same age (1951). Hornblende and less commonly magnetite are extensively altered in the B horizon of some podsol profiles (Matelski and Turk, 1947) developed in an area in northern Michigan probably covered by ice 11,000 years ago (Hough, 1958, p. 289 and table 22). Much hornblende and less hypersthene have been altered in the A horizon of a podsol profile developed on glacial till in eastern Quebec (Richard and Chandler, 1943) which may have weathered for 8000 to 10,000 years. On the other hand, the margins of feldspars and ferromagnesian minerals are only slightly altered in the fine-sand fraction of podsoils developed on Mankato (late Wisconsin) till in Manitoba, which may be roughly 13,000 years old (Hough, 1958, table 22). The contrast in weathering rate between most analyzed podsoils of the temperate climates and the volcanic-ash soils of St. Vincent is emphasized by slight degree to which hornblende, magnetite, and most labradorite are altered in late Pleistocene ash deposits which probably weathered for several tens of thousands of years.

The contrast in weathering rate between humid-temperate podsoils and volcanic-ash soils of St. Vincent and El Salvador can be explained in at least two ways. Probably most important is the acidity of podsoils, which commonly have a pH between 4 and 5 (Jenny, 1941). The pH of most volcanic-ash soils on St. Vincent is between 6 and 7 (Watson, et al., 1958). Activity of the hydrogen ion is one of the most important factors in hydrolysis of silicate minerals, for the weathering of a silicate mineral is largely a base-exchange reaction in which the hydrogen ion of water replaces a metallic cation of the silicate mineral (Frederickson, 1951). The equation for the initial step in hydrolysis of anorthite might be indicated as follows:



Conceivably the rapid decomposition of the glass may also retard the rate at which the minerals in volcanic-ash soils are altered. The readily-alterable glass may utilize the bulk of excess hydrogen ions in decomposition to halloysite and allophane, thus reducing the supply available for hydrolysis of the silicate minerals. Decomposition of the glass also liberates cations into the weathering system, which, unless quickly washed out of the soil, will probably retard

hydrolysis of the minerals. Addition of calcium ions, for example, should retard the alteration of anorthite as described in the equation above. The glass pellicles enclosing most crystals in the ash deposits probably did not substantially retard their hydrolysis by physically protecting the crystals against soil moisture. As proof of this, the fractured surfaces of crystals are etched to the same degree as crystal faces on the same grains which were originally coated with glass.

This discussion should not be interpreted as proving that rocks are decomposed more rapidly by podsolization in temperate climates than by weathering in the humid tropics. Minerals are highly altered chiefly in rather thin horizons of the post-glacial profiles mentioned above, whereas on St. Vincent the effects of weathering are nearly uniform through a rather thick B horizon. As an example, hypersthene is highly altered in an A horizon 5-8 inches thick in the Quebec podsol (Richard and Chandler, 1943), and slightly altered through a thickness of 4-8 feet on St. Vincent. The volume of hypersthene destroyed on St. Vincent may equal or even exceed that in the Quebec podsol. The Quebec podsol is probably older than the soil of St. Vincent, hence the total amount of minerals destroyed per thousand years on St. Vincent probably exceeded that in the podsol, even though individual grains were altered more rapidly in the latter.

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REFERENCES

- Anderson, R. M., 1938, *The St. Vincent Handbook*, 5th ed.: Kingstown, St. Vincent, 453 p.
- Barshad, I., 1958, Factors affecting clay formation: 6th Natl. Conf. on Clays and clay minerals, Proc., p. 110-132.
- Birrell, K. S. and Fieldes, M., 1952, Allophane in volcanic ash soils: *Jour. Soil Sci.*, v. 3, p. 156-166.
- Dickson, B. A., and Crocker, R. L., 1953, A chronosequence of soils and vegetation near Mt. Shasta, California: I. Definition of the ecosystem investigated and features of the plant succession: *Jour. Soil Sci.*, v. 4, p. 123-141.
- , 1954, A chronosequence of soils and vegetation near Mount Shasta, California: III. Some properties of the mineral soils: *Jour. Soil Sci.*, v. 5, p. 173-191.
- Ehrlich, W. A. and Rice, H. M., 1955, Postglacial weathering of Mankato till in Manitoba: *Jour. Geology*, v. 63, p. 527-537.
- Frederickson, A. F., 1951, Mechanism of weathering: *Geol. Soc. America Bull.*, v. 62, p. 221-232.
- Hardy, F., Robinson, C. K., and Rodriguez, G., 1934, *Studies in West Indian soils. VIII. The Agricultural soils of St. Vincent: Tropical Agriculture*, v. 11, p. 3-44.
- Hay, R. L., 1959a, Origin and weathering of late Pleistocene ash deposits of *St. Vincent*. B.W.I. *Jour. Geology*, v. 67, p. 65-87.

- Hay, R. L., 1959b, Formation of the crystal-rich glowing avalanche deposits of St. Vincent, B.W.I.: Jour. Geology, v. 67, p. 540-562.
- Hough, J. L., 1958, Geology of the Great Lakes: Chicago, University of Illinois Press, 313 p.
- Jenny, H., 1941, Factors of soil formation: New York, McGraw-Hill Book Co., Inc., 281 p.
- Kanno, I., 1956, A pedological investigation of Japanese volcanic-ash soils: 6th Internat. Cong. Soil Sci., Rapp., v. E., p. 105-109.
- Kubiěna, W. L., 1953, Bestimmungsbuch und systematik der Böden Europas: Stuttgart, Ferdinand Enke Verlag, 392 p.
- Matelski, R. P. and Turk, L. M., 1947, Heavy minerals in some podsol profiles in Michigan: Soil Sci., v. 64, p. 469-487.
- Richard, T. A. and Chandler, R. F., Jr., 1943, Some physical and chemical properties of mature podsol profiles: Soil Sci. America Proc., v. 8, p. 379-383.
- Sudo, T., 1954, Clay mineralogical aspects of the alteration of volcanic glass in Japan: Clay Minerals Bull., v. 2, p. 96-106.
- Tröger, W. E., 1956, Optische Bestimmung der gesteinsbildenden Minerale, Teil 1, Bestimmungstabellen: Stuttgart, E. Schweizerbart'sche Verlag., 147 p.
- Watson, J. P., Spector, J. and Jones, T. A., 1958, Soil and Land-use Surveys, No. 3, St. Vincent: Trinidad, Imp. Coll. of Tropical Agriculture, p. 1-70.
- Weyl, R., 1951, Schwermineralverwitterung in schleswig-holsteinischen Böden: Naturwiss. Ver. für Schleswig-Holstein, Schr., v. 25, p. 157-165.
- , 1952, Schwermineraluntersuchungen an Böden des württembergischen Unterlandes: Neues Jahrb. Geologie u. Paläontologie Abh., Monatshefte, p. 482-499.
- , 1954, Beiträge zur Geologie El Salvador, IV, Die Bimaschen in der Umgebung San Salvador: Neues Jahrb. Geologie u. Paläontologie Abh., Monatshefte, p. 49-70.
- Williams, H. and Meyer-Abich, H., 1955, Volcanism in the southern part of El Salvador: Univ. of Calif. Pub. Geol. Sci., v. 32, p. 1-64.