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# DIFFERENCES IN PARTICLE SIZE DISTRIBUTION AND MINERALOGY IN SOIL CATENAS IN SINGAPORE

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*RESUME*

*La taille des éléments, les minéraux de la fraction sableuse et argileuse, la micromorphologie des sols de trois toposéquences sont décrites. La fraction des sables grossiers consiste principalement en quartz; la plupart des minéraux lourds présents sont des minéraux ferrugineux d'origine secondaire. Les concentrations en minéraux lourds se trouvent à proximité de la surface. La fraction argileuse est dominée par la kaolinite et la gibbsite, cette dernière augmentant avec la profondeur. Les profils bien drainés ont un indice de différenciation texturale plus grand que 1,2 et leur horizon B présente 2 à 3 % de cutanes : un horizon argillique est donc présent. Les processus responsables de ces caractéristiques sont une altération chimique intense associée avec une migration de l'argile. L'évolution de la toposéquence peut être expliquée, pour autant qu'il y ait eu stabilité, comme le résultat de processus encore actifs à l'heure actuelle.*

*ABSTRACT*

*The particule-size, sand-sized minerals, clay minerals and micromorphology of soils on three catenas are described. The coarse sand fraction consists mainly of quartz; most heavy minerals present are iron minerals of secondary origin. Concentrations of heavy minerals are highest close to the ground surface. The fine clay fraction is dominated by kaolinite and gibbsite, the latter increasing with depth. Freely drained profiles have an index of textural differentiation greater than 1.2 and their B horizons have 2 - 3 percent cutans; an argillic horizon is thus present. Processes causing these features are intense weathering coupled with clay translocation. The evolution of the catena can be explained in steady-state terms, as a result of processes active at the present day.*

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# INTRODUCTION AND AIMS

This is a study of the differences in particle-size within soil catenas, together with associated features of mineralogy and micromorphology. Its aim is to elucidate the weathering and physical translocation of the mineral constituents of the soil, with particular attention to the presence of illuvial clay. Rather than considering individual profiles, the unit of study taken is the soil catena. This enables attention to be given to both the nature of the difference in particle-size distribution from the crest to the base of the slope, and the extent to which processes acting laterally down the slope have contributed to their formation. In order to isolate the effects of relief, a small area was selected with all other soil-forming factors within this area are nearly uniform.

The catena studied lies in the evergreen rain forest climatic zone, the *inner core* of the humid tropics (DOUGLAS, 1969). The special features of this environment have attracted the attention of both ecologists and geomorphologists. The ecological interest arises from the existence of a mature, stable and sometimes undisturbed ecosystem. The particular geomorphical interest is that it is one of the few morphoclimatic zones where the present landforms are believed to result from the action of geomorphological processes of similar nature and intensity to those found at the present day, without forms inherited from different climates in the past (DOUGLAS, 1969). These features of interest apply equally to the soils; it is possible that the present soil morphology developed under similar climatic conditions to those of today, and that the soil is at least mature and possibly in a steady state.

## Environment.

The study area lies in the centre of Singapore Island. The climate is typical of the hot and permanently-humid, or equatorial, type; mean annual temperature is 26.7° C with little variation through the year, and mean annual rainfall 2600 mm with no dry months (NIEUWOLT, 1965). Although average rainfall exceeds average potential evapotranspiration for all months, there are several months in which periods of water deficit occur in some years (NIEUWOLT, 1965). The three catenas studied lie within an area of under 1 km$^2$ and their relative relief is less than 70 m. No appreciable internal climatic differences can be assumed due to the above factors. All are on a similar rock type, namely granodiorite

(HUTCHINSON, 1964). The whole area was formerly covered by lowland evergreen rainforest characterized by *Dipterocarpus* spp., now converted to pasture grassland.

Thus the soil forming factors of climate, parent material, vegetation and time are all relatively uniform, and the observed soil differences along the slopes may be expected to result from the factor of relief and its consequences for soil moisture and surface processes.

The catenas are developed on granodiorite, which has medium to coarse structure, and mainly consists of quartz, alkali feldspar, plagioclase feldspar and biotite, with tourmaline, zircon, rutile, hornblende, epidote and garnet as the major accessory heavy minerals (NOSSIN & LEVELT, 1967).

The catenas studied are all valley-side slopes of 80 - 120 m length (Fig. 1). Catenas 1 and 2 have similar average gradients (8.4° and 9.2° respectively) whilst catena 3 is steeper (average 17.2°) and has a stepped profile form. All show a feature characteristic of the rain-forest morphoclimatic zone (BIROT, 1960, 1968), an abrupt change in angle separating the main, freely-drained part of the slope from the lowest part with drainage impedence. These will be termed the upper slope and basal area respectively, separated by the basal break of slope.

The upper slope of all three catenas carries a yellowish, strongly-leached clay soil, formerly called in Malaya a *red-yellow laterite soil* (PANTON, 1965). It has until recently been a common assumption that such freely-drained, strongly leached soils of the rainforest zone belong to the class of ferralsols on the F.A.O. legend (F.A.O. 1974) and oxisols in the U.S. taxonomy (Soil Survey Staff, 1975). Some recent investigations within this same climatic region have shown that soils formerly assumed to be ferralsols/oxisols do in fact fulfil the criteria for classification as acrisols (F.A.O.) or ultisols (U.S.). The correct classification of the present upper-slope soils is discussed below.

The typical soil profile of the upper slope is as follows :

- Ah 0 - 20 cm : Dark brown (10 YR 3/3), sandy clay loam, crumb structure, almost loose consistance, many roots and insect burrows, clear boundary.
- Ab 20 - 65 cm : Brownish yellow (10 YR 6/6), sandy clay loam, very weak, angular blacky structure, no clay skins, very friable, few roots, merging boundary.

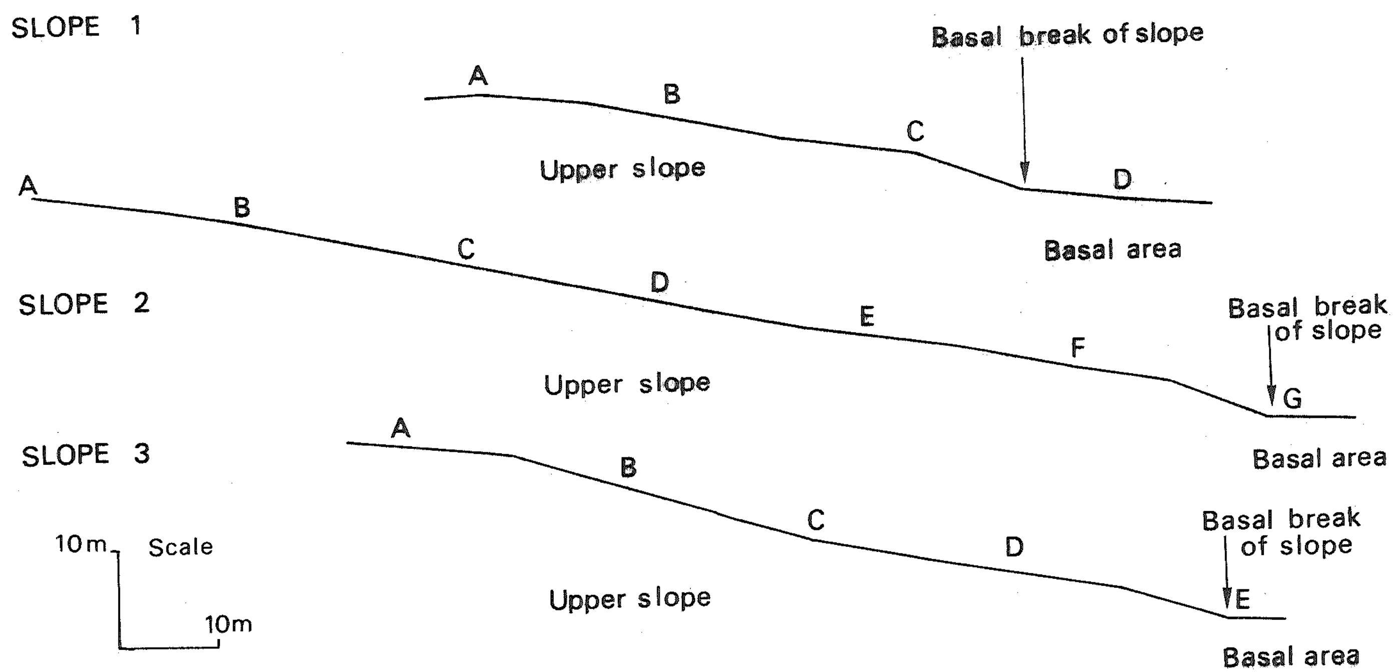


Fig. 1 : Slope form and terminology. Letters indicate sites of soil profiles.

- Bt 65 - 120 cm : Reddish yellow (7.5 YR 6/8), heavy clay, angular blocky structure, weakly developed clay skins, friable, few roots, merging boundary.
- BC 120 - 255 cm : Red (2.5 YR 5/8), very weak angular blocky structure, firm, very few roots, mottles from weathered rock increasing toward base.

The basal area has a poorly-drained greyish and more sandy soil, classified as gley or its equivalent in other systems (e.g. F.A.O. gleysol). The typical profile of this soil is as follows :

- Ah 0 - 9 cm : Dark brown (10 YR 3/3), sandy loam, very weak crumb structure, many roots and insect burrows, clear boundary.
- A2 0 - 40 cm : Yellow (10 YR 7/8) with abundant medium greyish brown (10 YR 5/2) mottles, silty clay loam, massive structure, soft, plastic, some roots, clear boundary.
- Bgj 40 - 85 cm : Dark greyish brown (10 YR 4/2), mixed with reddish brown (5 YR 4/3) mottles, sandy clay, massive structure, soft, plastic, some roots, clear boundary.
- G 85 - 165 cm : Grey (7.5 YR 6/0), with abundant large prominent dark greyish brown (10 YR 4/2) mottles, sandy loam, angular blocky structure, soft, very few roots.

The environmental conditions suggest two likely circumstances with respect to processes. First, the high temperature coupled with high humidity of the soils for all the year except irregular short periods presuppose the likelihood of a high intensity of weathering. Secondly, the profiles are observed in the field to have a moderate to high permeability, and as rainfall exceeds evapotranspiration throughout the year, a high intensity of leaching may also be expected. These a priori expectations will be set against the observed features of the profiles.

## METHODS

In order to permit the objective study of soil layers and their catenary variation, soil inspection sites were chosen at regular 20 m intervals and samples taken at the following standard depths (± 5 cm) : 10, 20, 30, 45, 60, 75, 90, 120 and 150 cm. *Layer* is used here deliberately to mean a zone at specific depth in order to differentiate from *horizon*, which has its standard meaning. A total of 144 samples were collected from 16 soil profile sites. In three of the profiles, undisturbed samples for making thin sections were collected at 30, 60, 90 and 120 cm.

Laboratory analysis included granulometric analysis, heavy mineral analysis, X-ray diffraction of the fine clay fraction (< 1 μm) and micromorphological examination.

Granulometric analysis.

This was carried out by sieve and pipette methods. The fine clay fraction (< 1 μm) collected from sedimentation was used for X-ray diffraction.

X-ray diffraction.

Clay samples were ground with acetone and mounted on glass slides. X-ray diffraction was carried out at a full speed of 1° per minute from 4° - 40° with cobalt radiation. The intensities of the minerals are expressed in relative terms viz. dominant, common, few and trace only.

Heavy minerals.

The coarse sand fraction (about 20 g) was isolated, separated into heavy and light minerals with bromoform, and the heavy minerals (between 200 - 500 grains) examined under both binocular and petrographic microscopes; minerals were divided into opaque and non-opaque, then identified and counted.

Micromorphology.

Undisturbed samples were dried very slowly and impregnated by Vestopal resin. The impregnated blocks were sectioned, ground, polished, cleaned and mounted. The mounting blocks were then cut off and the slides ground down to 30 - 40 μm thick. Quantitative micromorphological data were obtained by the point-count method, counting a 1500 - 2000 points per thin section.

## RESULTS

Differences in particle-size distribution.

The mean feature of particle-size distribution in nearly all samples is the presence of two maxima, in the coarse sand and clay fractions, with a minimum in the silt fraction (Fig. 2). This is a normal feature of

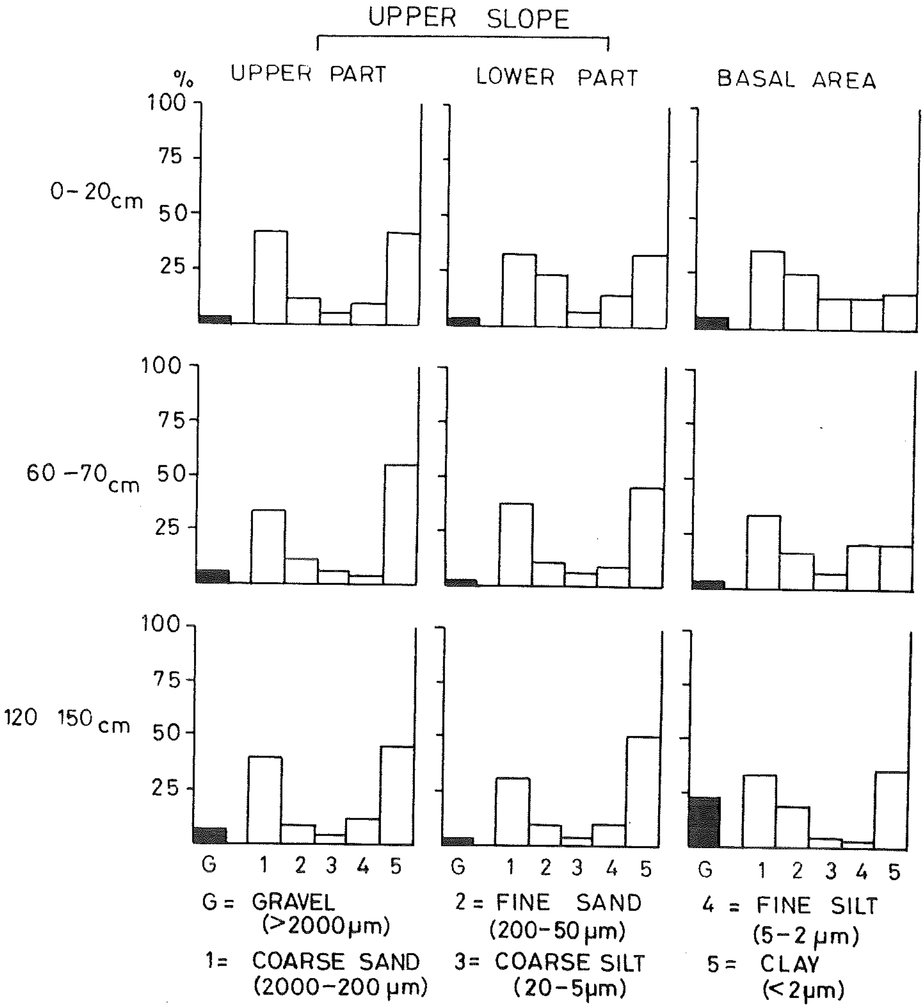


Fig. 2 : Particle-size distribution. Values for the three slopes have been combined and averaged.

soil derived on granodiorite in the humid tropics (AGYEPONG, 1971). The sand, silt and clay contents of all the layers in the three catenas average close to 50, 10 and 40 percent respectively. Silt content remains relatively constant, ranging between 8 and 16 percent, therefore particle-size distribution is mostly due to changes in the relative proportions of clay and sand. An exception is one sample from the basal area of slope 2, with a silt content of more than 40 percent.

The maximum sand and minimum clay contents occur in the surface layer where sand is usually over 55 percent. There is a decrease in sand

and increase in clay with depth; the maximum clay content occurs at a depth of about 60 - 75 cm, below which it decreases again. The maximum sand contents are not always in the uppermost layer but vary from 10 to 35 cm depth. It shows no relation to position on the slope.

The basal areas have more sandy textures than the upper slopes and increase of clay with depth is less pronounced.

Fine clay (< 1 μm) forms between 0.65 and 0.98 of total clay. This ratio shows no relation to slope gradient or position in the catena.

A distinction will be made between a textural B horizon and an argillic horizon (F.A.O., 1974), the former being defined only on the basis of particle-size distribution, the latter requiring in addition evidence of illuvial clay. A textural B horizon is defined here as any layer which has 8 percent more clay than that found at 10 cm depth. On the basis of this definition, textural B horizons exist in most profiles (Fig. 3). The depth at which the textural B horizon begins is generally 30 - 45 cm and shows no relation with catenary position. The decrease in clay from the more sandy surface layer to the textural B horizon is usually abrupt, changing by about 10 percent within 10 cm. Below the textural B horizon, the decrease in clay is more gradual, usually less than 5 percent per 10 cm. The thickness of the textural B horizon shows some tendency to be less near the crest of the slope than in other positions.

Another way to describe the degree of textural differentiation in a soil profile is the index of textural differentiation, $I_T$, where

$$I_T = \frac{\text{percentage clay in the maximum clay content layer}}{\text{percentage clay in the 0 - 10 cm layer}}$$

The index of textural differentiation (Fig. 4) is relatively constant (1.2 - 1.7) on the uppermost three profile sites on each catena, and rises to 1.8 or greater in the basal area.

Heavy mineral in the coarse sand fraction.

The heavy mineral contents of the soils throughout the catenas are very low, the greater part of the coarse sand fraction being composed of quartz (Tab. I). The highest content occurs either at the surface, or at 20 or 30 cm depth; below this the amounts of heavy minerals fall, sometimes rising again below 75 cm. The deeper layers of the basal areas have

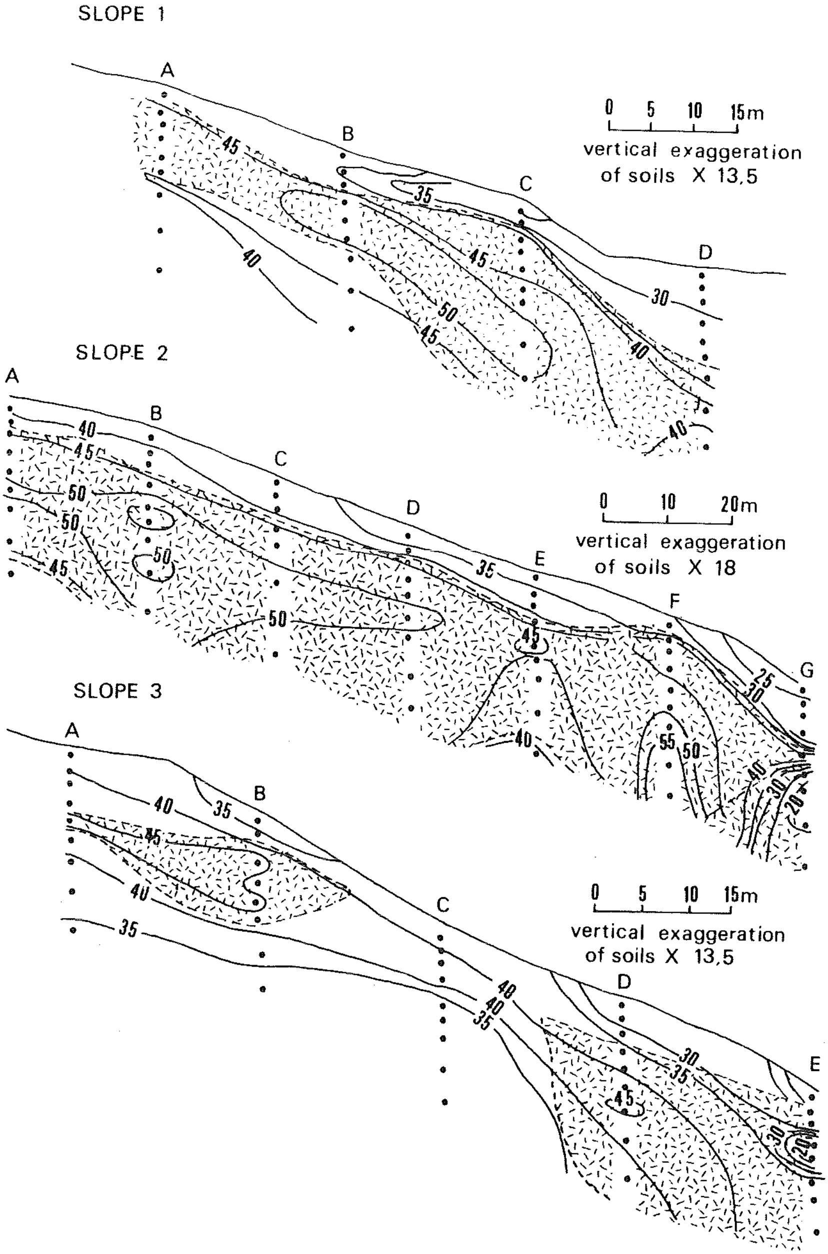


Fig. 3 : Isopleth diagrams of clay percentages. Points indicate sample locations. The shaded area is the textural B horizon.

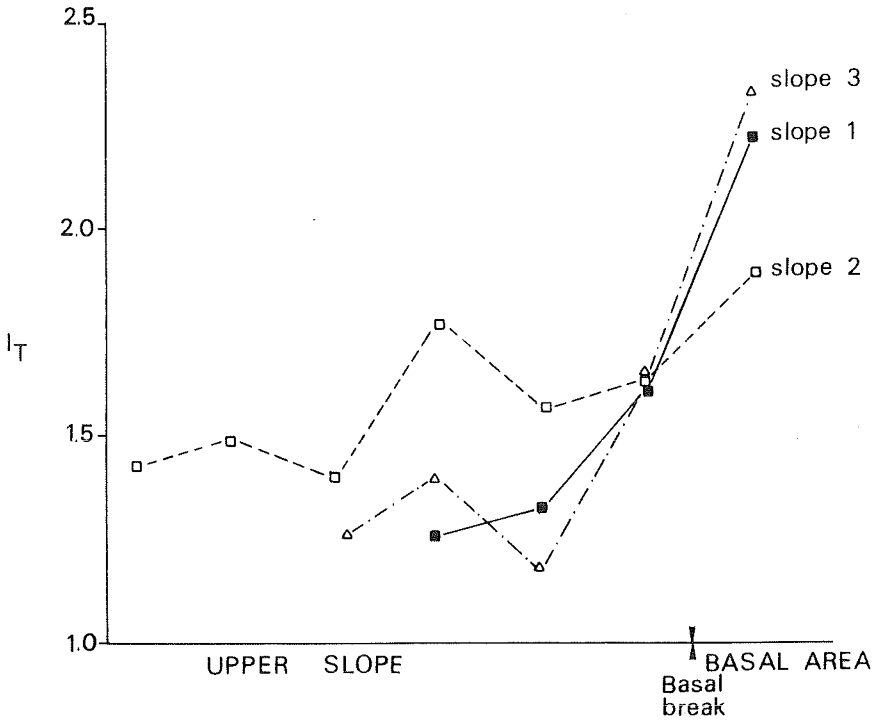


Fig. 4 : Index of textural differentiation.

a lower heavy mineral content then those of the upper slope, except in slope n° 3.

Opaque minerals constitute over 75 percent of the heavy minerals. Haematite is dominant and goethite the second most frequent opaque mineral. The most abundant non-opaque heavy minerals are zircon and tourmaline. Their content reaches a maximum at 10 - 30 cm, followed by a decrease with depth. Amounts are slightly lower in the basal area than on the upper slope (Tab. II). Epidote and garnet are rare, and occur respectively in only one of third and one quarter of the samples.

Slope 1.

| cm | A | B | C | D |
|---|---|---|---|---|
| 10 | .057 | .321 | .018 | .047 |
| 20 | .097 | .058 | .045 | .053 |
| 30 | .065 | .044 | .013 | .012 |
| 45 | .077 | .041 | .012 | .035 |
| 60 | .072 | .022 | .015 | .022 |
| 75 | .080 | .059 | .058 | .020 |
| 90 | .005 | .246 | .043 | .025 |
| 120 | .014 | .246 | .012 | .030 |
| 150 | .144 | .232 | .027 | .013 |

Slope 2.

| cm | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 10 | .211 | .118 | .077 | .114 | .181 | .909 | .247 |
| 20 | .124 | .180 | .107 | .108 | .067 | .094 | .182 |
| 30 | .046 | .020 | .042 | .104 | .057 | .064 | .198 |
| 45 | .028 | .019 | .012 | .019 | .012 | .067 | .021 |
| 60 | .024 | .028 | .024 | .021 | .019 | .171 | .052 |
| 75 | .023 | .016 | .014 | .017 | .018 | .022 | .018 |
| 90 | .013 | .025 | .019 | .010 | .020 | .013 | .025 |
| 120 | .058 | .006 | .007 | .006 | .024 | .030 | .021 |
| 150 | .019 | .020 | .016 | .021 | .029 | .021 | .021 |

Slope 3.

| cm | A | B | C | D | E |
|---|---|---|---|---|---|
| 10 | .378 | .122 | .056 | .176 | .206 |
| 20 | .375 | .072 | .045 | .176 | .120 |
| 30 | .304 | .113 | .031 | .069 | .113 |
| 45 | .370 | .048 | .043 | .018 | .077 |
| 60 | .239 | .069 | .022 | .063 | .014 |
| 75 | 1.307 | 1.231 | .057 | .064 | .035 |
| 90 | .075 | .090 | .087 | .212 | .192 |
| 120 | .067 | .051 | .146 | .162 | .086 |
| 150 | .043 | .031 | .069 | .064 | .0184 |

Tab. I : Distribution of heavy minerals, as percentage by weight of the coarse sand fraction.

Slope 1.

| | A | | B | | C | | D | |
|---|---|---|---|---|---|---|---|---|
| cm | R | M | R | M | R | M | R | M |
| 10 | 209 | 0 | 226 | 0 | 170 | 0 | 196 | 0 |
| 20 | 456 | 25 | 247 | 0 | 236 | 10 | 144 | 0 |
| 30 | 185 | 0 | 213 | 12 | 140 | 0 | 79 | 0 |
| 45 | 125 | 0 | 202 | 24 | 191 | 11 | 18 | 0 |
| 60 | 101 | 10 | 141 | 0 | 123 | 11 | 61 | 0 |
| 75 | 68 | 46 | 125 | 0 | 156 | 24 | 23 | 0 |
| 90 | 31 | 0 | 39 | 0 | 152 | 12 | 63 | 0 |
| 120 | 41 | 21 | 106 | 0 | 162 | 75 | 40 | 0 |
| 150 | 20 | 0 | 55 | 11 | 140 | 13 | 36 | 0 |

Slope 2.

| | A | | B | | C | | D | | E | | F | | G | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| cm | R | M | R | M | R | M | R | M | R | M | R | M | R | M |
| 10 | 204 | 0 | 231 | 0 | 216 | 0 | 146 | 0 | 152 | 0 | 268 | 0 | 132 | 13 |
| 20 | 193 | 12 | 259 | 12 | 153 | 0 | 193 | 20 | 202 | 0 | 205 | 11 | 139 | 23 |
| 30 | 135 | 13 | 197 | 0 | 125 | 0 | 190 | 12 | 184 | 11 | 172 | 0 | 194 | 39 |
| 45 | 105 | 12 | 114 | 11 | 198 | 0 | 169 | 0 | 168 | 11 | 91 | 63 | 166 | 126 |
| 60 | 84 | 0 | 110 | 0 | 204 | 0 | 105 | 0 | 174 | 0 | 80 | 64 | 167 | 128 |
| 75 | 74 | 0 | 112 | 0 | 138 | 14 | 120 | 0 | 175 | 0 | 89 | 14 | 81 | 0 |
| 90 | 62 | 0 | 33 | 0 | 146 | 30 | 72 | 11 | 58 | 10 | 99 | 30 | 96 | 0 |
| 120 | 109 | 21 | 78 | 10 | 149 | 21 | 30 | 0 | 59 | 20 | 163 | 21 | 69 | 9 |
| 150 | 10 | 0 | 31 | 0 | 78 | 10 | 62 | 0 | 83 | 20 | 123 | 10 | 50 | 3 |

Slope 3.

| | A | | B | | C | | D | | E | |
|---|---|---|---|---|---|---|---|---|---|---|
| cm | R | M | R | M | R | M | R | M | R | M |
| 10 | 227 | 11 | 239 | 13 | 201 | 12 | 330 | 0 | 125 | 19 |
| 20 | 324 | 0 | 303 | 41 | 202 | 47 | 355 | 48 | 130 | 0 |
| 30 | 304 | 0 | 205 | 45 | 194 | 22 | 303 | 25 | 167 | 0 |
| 45 | 135 | 13 | 110 | 14 | 139 | 29 | 262 | 12 | 88 | 13 |
| 60 | 141 | 0 | 55 | 12 | 56 | 28 | 254 | 0 | 50 | 0 |
| 75 | 45 | 0 | 91 | 0 | 54 | 0 | 177 | 0 | 22 | 0 |
| 90 | 58 | 19 | 58 | 17 | 56 | 0 | 131 | 0 | 68 | 0 |
| 120 | 49 | 0 | 35 | 26 | 57 | 0 | 87 | 0 | 12 | 0 |
| 150 | 27 | 0 | 61 | 34 | 21 | 9 | 114 | 10 | 14 | 0 |

Tab. II : Total counts of resistant minerals and moderately resistant minerals par 100 g of coarse sand on three slopes. R : resistant minerals (zircon + tourmaline), M : moderate resistant minerals (epidote + garnet).

The absence of primary weatherable minerals, scarcity of moderately resistant minerals (epidote and garnet) and dominance by highly resistant minerals (zircon and tourmaline) and secondary minerals (haematite, goethite and leucoxene) is an indication of an intense degree of weathering in the soils; whilst some of the opaque minerals (magnetite, ilmenite) are present in the parent rock, most are of secondary formation. Their frequency is associated with the presence of iron concretions in the gravel fraction; in particular, haematite of coarse sand size appears to be formed along with gravel-sized iron concretions.

The non-opaque minerals are dominated by zircon and tourmaline in all layers. Their proportions differ little down to bedrock; the small difference in the proportion between zircon and tourmaline have been reported by NOSSIN & LEVELT (1967) in granodiorite in an adjacent area.

An accumulation of heavy minerals in the surface layers has been reported previously (McCALLIEN *et al.*, 1964; AGYEPONG, 1971), suggesting that it may be a widespread feature on igneous materials in the humid tropics. Of the alternative possible explanations, the most likely is that intense weathering near the surface has destroyed less resistant minerals, such as feldspars, epidote and garnet, and altered other minerals, such as ilmenite to leucoxene and some haematite to goethite. The highly resistant zircon and tourmaline remain.

Relative weathering intensities may be estimated using the principles that higher relative amounts of very resistant minerals (here zircon plus tourmaline) and lower absolute amounts of moderately resistant minerals (here epidote plus garnet) indicate more intense weathering. On the upper slope, relative amounts of very resistant minerals show an overall decrease with depth but with appreciable irregularities; these latter could be caused by patches of less highly-weathered regolith remaining on sites of former core-stones. Results for the basal areas show higher relative amounts of very resistant minerals and lower absolute amounts of moderately resistant minerals, (except in slope 2), suggesting overall more intense weathering.

Mineralogy of the fine clay fraction.

The samples from profile 2, slope 1 were examined : soil samples from 60 cm and 100 cm depth and highly weathered rock from 400 cm (Fig. 5). The clay minerals present are kaolinite and gibbsite, both very poorly crystalline, indicating soils of advance stage of chemical

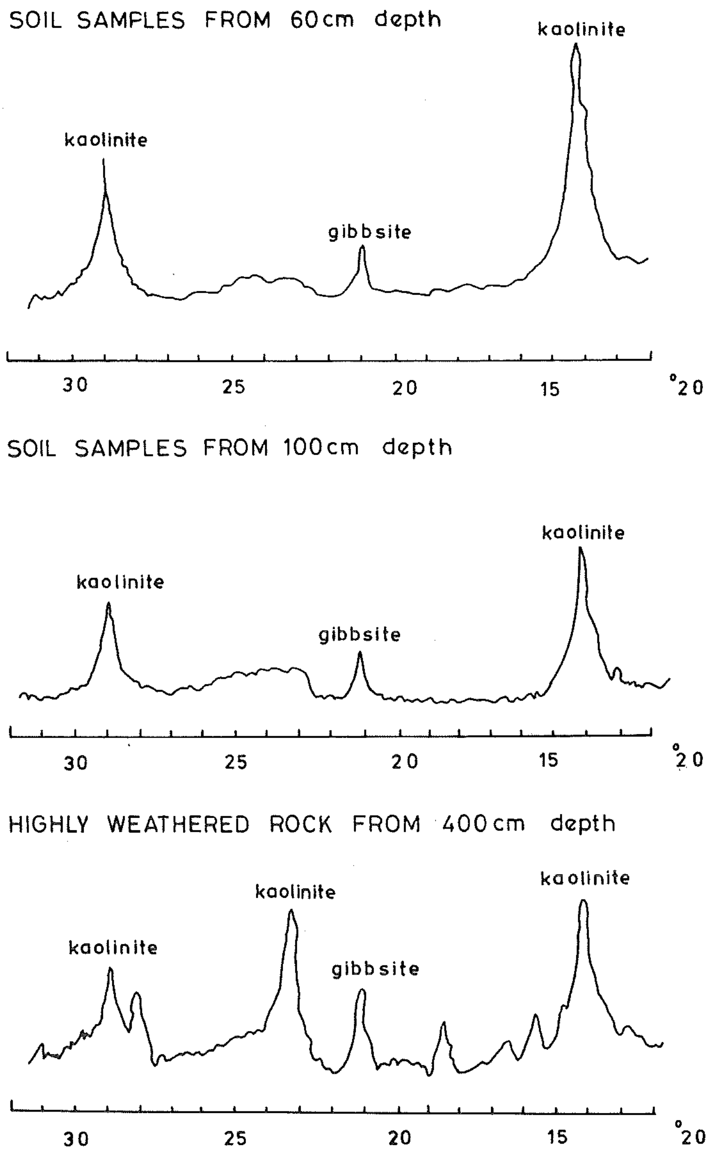


Fig. 5 : X-ray diffraction traces of the finer clay fraction from profile 2, catena n° 1.

weathering (JACKSON & SHERMAN, 1953). The amount of kaolinite remains fairly constant, but gibbsite increases with depth. A similar trend was observed in most profiles in the upper slope of three catenas, except in slope 3 where the amount of kaolinite decreases slightly with depth (Tab. III).

Slope 1.

| | A | | B | | C | | D | |
|---|---|---|---|---|---|---|---|---|
| cm | k | gi | k | gi | k | gi | k | gi |
| 10 | d | t | d | t | d | u | d | u |
| 60 | d | t | d | t | d | u | d | u |
| 150 | c | f | d | f | d | t | d | u |

Slope 2.

| | A | | B | | C | | D | | E | | F | | G | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| cm | k | gi | k | gi | k | gi | k | gi | k | gi | k | gi | k | gi |
| 10 | d | t | d | t | d | t | d | t | d | u | d | u | d | u |
| 60 | d | t | d | f | d | f | d | t | d | u | d | u | d | u |
| 150 | d | f | d | f | d | f | d | f | d | u | d | u | d | u |

Slope 3.

| | A | | B | | C | | D | | E | |
|---|---|---|---|---|---|---|---|---|---|---|
| cm | k | gi | k | gi | k | gi | k | gi | k | gi |
| 10 | d | f | d | f | d | f | d | u | d | u |
| 60 | c | c | c | c | c | c | d | u | d | u |
| 150 | c | c | c | c | c | c | d | f | d | u |

Tab. III : Clay mineral frequency in the fine clay fraction. k : kaolinite, gi : gibbsite, d : dominant, c : common, f : few, t : trace, u : untraceable.

The clay minerals are dominated by kaolinite throughout the catenas and with moderate amount of gibbsite in the upper slope, the latter becoming untraceable in the lower part of the upper slope and in the basal area. This distribution is different from Tardy's model (TARDY *et al.*, 1973) in which under a similar climate, gibbsite dominated on the upper slope and kaolinite on the lower slope and basal area.

Evidence of illuvial clay.

Cutans can be observed in the field by eye in some of the B horizons; these are shiny and sometimes the colour is lighter than the soil matrix. They occur on the surfaces of peds and the walls of root channels.

Study of these cutans on thin section shows that they have a clear layered structure and absence of coarse material, while in cross polarized light they are anisotropic. These feature indicates that they are formed by illuviation of clay particles.

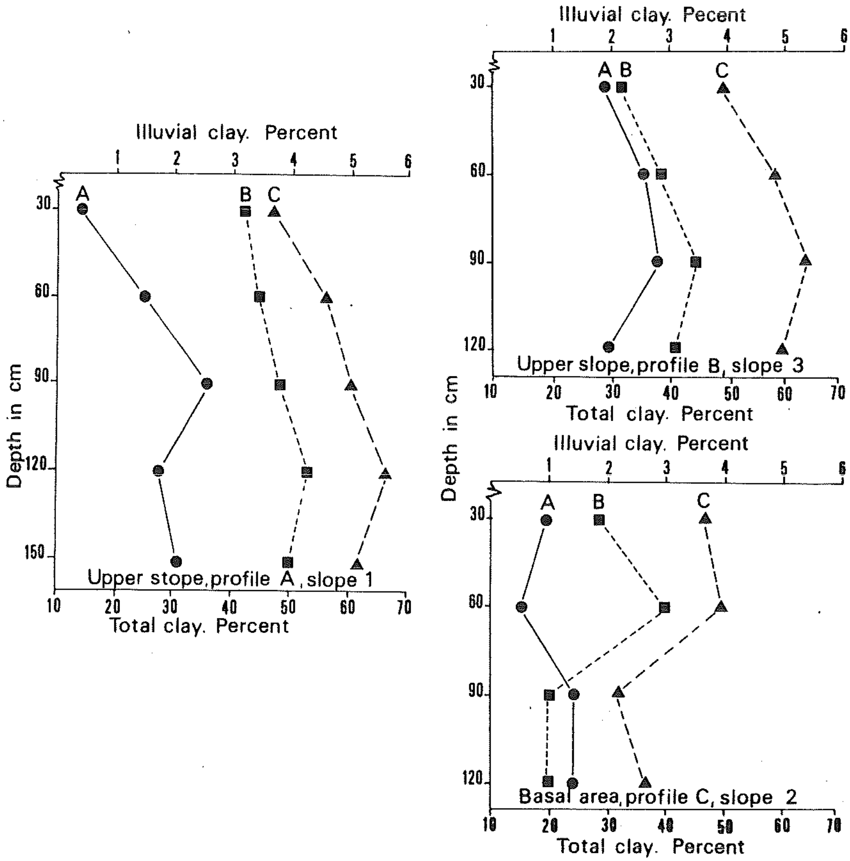


Fig. 6 : Percentages of illuvial clay (A), total by granulometric analysis (B) and total clay by micromorphological analysis (C).

The amounts of cutans on thin sections estimated by the point-count method, are shown in figure 6. Cutans average 2 percent in the two profiles from the upper slope and 1 percent in that from the basal area. On the upper slope the increase with depth of illuviation cutans is associated with the amount of total clay, as estimated by both micromorphological and granulometric analyses. There is no such relation in the basal area.

These results suggest that with poorer drainage, cutan formation is reduced. This does not necessary imply that clay translocation is reduced as not all the clay is translocated appears in thin section as birefrigent cutans (ESWARAN, 1968). Cutans will not appear in those profiles which are continuously wet; there must be a period of dryness for the illuviated materials to adhere to natural surfaces and become oriented. The upper slope of present catenas have such drying periods, due to periodic soil moisture deficits.

In addition to cutans, an abundance of birefringent domains have been found inside the soil matrix. These domains may result from the destruction of former cutanic material, either by termite activity and/or by drying and wetting, embedding the old cutanic material into soil matrix as suggested by STOOPS (1968).

Luvans, which occur on the outer surfaces of peds, contain less clay than the ped interior and are formed by the differential removal of materials by percolating water, are found in the upper layers of basal area but not in the upper slope. This may be because the effect of differential removal of fine clay on the basal area is easy to observe with the high silt content, whereas in the upper slope this is not easily observed owing to the lesser amount of silt and more clay.

## DISCUSSION

The bimodal frequency distribution of particle size is a normal feature of soils on granodiorite under tropical rain forest. Under the intensive weathering conditions most of the less resistant minerals. Such as feldspar and biotite, are quickly reduced into clay size whilst quartz remains as coarse sand particles. The facts that the sand fraction seen in thin section is dominated by quartz, that no weatherable minerals are observed in the heavy minerals in coarse sand fraction and that the clay minerals are dominated by poorly crystallized kaolinite and gibbsite supports this explanation.

The existence of a more sandy surface layer is attributed mainly to eluviation of clay, both vertical and lateral. Evidence in support of this is the presence of illuvial clay beneath, the existence of luvans in the surface layer, and the fact that fine clay forms a lower proportion of total clay in the surface layer than in deeper horizons.

Lighter textures occur in the basal areas of the slopes, with a higher silt content as well as sand. This may be due in part to colluvial deposition of coarser fractions, with clay being differentially carried onwards to the streams. A layered structure to the soil matrix observed in thin section of upper layer of the basal area supports this hypothesis.

An argillic horizon is an illuvial horizon in which layer-lattice clay have accumulated by illuviation to a significant extent. As defined by the F.A.O. (1974), the two criteria are higher clay content in a subsurface horizon than above and/or the presence of evidence of illuvial clay in the form of visible clay skins or oriented domains in thin section.

The textural criterion, an index of textural differentiation of greater than 1.2, is exceeded in the upper slope profiles. Visible clay skins, whilst thin, are quite common in the lower parts of the textural B horizon. The minimum amount of oriented clay required is 1 percent. However, HILL (1970) has shown that there may be high within-sample variability. MIEDEMA & SLAGER (1972) suggested that a value of 1.6 percent is necessary in order to get 1 percent of illuviated cutans with 95 percent confidence.

The amount of clay cutans from the upper slope profiles in the present catenas is higher than both the 1 percent and the 1.6 percent limits. There is, however, a further aspect concerning the stability of clay cutans in these soils. Many scientists (e.g. ESWARAN & STOOPS, 1968) believe that clay cutans can be destroyed or entrapped and become part of the soil matrix. This feature is especially likely in soils with high biological activities. STOOPS (1968) also suggested that birefrigent domains are the residue of materials resulting from the destruction of cutans; such domains are common in the B horizons.

It is sometimes stated (e.g. BRIDGES, 1970) that clay translocation does not occur in soils under tropical rain forest, and that such soils show little variation in particle size distribution with depth.

Whilst this may be true of soils derived from fine-textured parent materials, especially those rich in ferromagnesian minerals, it is not the case over granodiorite. Both the present catenas and general observations in Malaysia and Singapore show that marked textural differentiation, with illuvial clay in the B horizon, occurs.

If it were true that because of the constantly wet climatic conditions under tropical rain forest, the soil did not become dry at any time, no illuviation could occur. However, soil moisture deficits do occur at irregular intervals (NIEUWOLT, 1965) and clay may be deposited in the subsoil during such periods.

From the above discussion, argillic horizons are present in the upper slope soils. This suggests that these soils are belong to the acrisols (F.A.O.) or ultisols (U.S.), and not to ferralsols (F.A.O.) and oxisols (U.S.). Evidence from heavy mineral analysis shows that intensity of weathering mostly decreases with depth. Irregularities in this pattern may be due to the effect of former core-stones. Under the rainforest climate, weathering of granitic rock at first follows the joints, separating into large blocks; weathering then attacks these blocks from the edges to the centres, producing core-stones (THOMAS, 1974). Where the core-stones have been reduced to soil, the degree of weathering will still be lower in the centres of former core-stone sites.

Explanations of catenary evolution can grouped into steady state and historical approaches. A steady state explanation means that the morphology of the catena is caused by the processes that are presently active, thus implying a stable environment. In the historical approach, the morphology is explained in terms of processes different in nature of intensity from those of the present (YOUNG, 1976, p. 275).

Studies of soil catenas in the tropics leave not infrequently invoke past climatic changes to explain the observed morphology (e.g. OLLIER, 1959 & WATSON, 1965). Most of these studies are based on the savanna zone of marginal areas of tropical rain forest, where it is known that substantial climatic changes have taken place.

However, the "inner core" of humid tropics, which includes Singapore, has been relatively unaffected by the events of Quaternary, and has experienced constant high temperatures and rainfall, and a dense vegetation cover. Periodicity in geomorphological and pedological processes in this zone has been restricted to minor variations in occurrence and intensity of precipitation (BUDEL, 1957). These conditions produce pedological stability.

On grounds of economy of scientific hypothesis, a steady state explanation is to be preferred unless there is evidence to the contrary. Many of the observed features can be explained by those processes acting at present. On environmental grounds a steady state hypothesis is also reasonable. For these reasons, therefore, a steady state explanation is given to account for the genesis of these soils.

## SUMMARY


The main differences in particle-size distribution and mineralogy in soil catenas formed on granodiorite under a rain forest climate in Singapore are as follows :

1. The main features of particle-size differences are the presence of sandy topsoils and heavier subsoils throughout the catena. The basal areas have more sandy textures than the upper slopes.

2. The coarse sand fraction consists mainly of quartz, and most of the heavy minerals present are iron minerals of secondary origin. Concentration of heavy minerals are highest close to the ground surface.

3. The fine clay fraction is dominated by kaolinite throughout the catenas, with moderate amounts of gibbsite in the upper slopes.

4. Freely drained soil profiles in the upper slopes have an index of textural differentiation higher than 1.2 and their B horizons have 2 - 3 percent illuvial cutans; an argillic horizon is thus present.

5. Processes causing these features are intense weathering coupled with clay translocation, and selective removal of clay.

6. Processes similar in kind and intensity for those acting at the present day are adequate to account for the observed morphology without the need to invoke past climatic changes. A steady state explanation can therefore account for the formation of these soils.


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