

WOSSAC: 25692  
631.473  
(911.2)

NOT FOR PUBLICATION

LABORATORY NOTE NO. LN/282/MJD.  
January, 1963.

BOR.63.  
B5573

DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

Road Research Laboratory

THE CLAY MINERALOGY OF SOME SOILS FROM NORTHERN BORNEO  
CONSIDERED IN RELATION TO THEIR ORIGIN AND THEIR  
PROPERTIES AS ROADMAKING MATERIALS

by

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### SUMMARY

This Note reports the results of mineralogical investigations, using X-ray and differential thermal analysis methods, of the clay mineral constitution of 34 samples of soil from northern Borneo collected in the course of a survey of roadmaking materials. The clay mineral constitution of the soils was related to the parent material on which they were formed, and to their physical properties. The hydrated iron and aluminium oxide contents of the clay fraction of the soils were also estimated quantitatively.

The clay fraction of residual soils formed on igneous rocks was mainly kaolin mineral, often with some hydrated halloysite, and sometimes vermiculite or chlorite. Soils formed on sedimentary deposits differed in containing a considerable amount of clay mica (illite, or less commonly muscovite), although sometimes illite gave place to chlorite or vermiculite at the top of the profile. Kaolinite was again present, often as a major constituent, and also small proportions of chlorite and vermiculite, but hydrated halloysite was not observed. None of the soils examined contained a preponderance of montmorillonite, and a considerable amount was observed in only one profile, developed on basic igneous rock.

Of the soils falling above the A-line on the Casagrande classification chart (the region in which the results for many clay soils fall), those containing considerable montmorillonite had the highest values of liquid limit and plasticity index, those containing both kaolinite and illite had the lowest values, and those containing mainly illite had intermediate values. This is as would be expected from the values usually quoted for pure clay minerals. However, the profile containing mainly kaolinite gave values tending to be higher than that containing mainly illite, perhaps due to the crystallographically disordered state of the kaolinite in this profile.

Soils in which some hydrated halloysite was found all fell below the A-line (the region where silty soils usually fall), those with the highest clay content having a plastic limit of about 70 per cent and a liquid limit of about 105 per cent. Soils containing muscovite also fell below the A-line, but these, and other soils falling in the same area of the chart, also had high silt contents.

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Introduction

In 1960 Messrs. Clare and Beaven of the Road Research Laboratory visited Sarawak, North Borneo and Brunei to study the roadmaking materials in northern Borneo. They have described the geology and topography of the country<sup>(1)(2)(3)</sup>, and note that the soils are important roadmaking materials due to the limited resources of good quality roadstone. They suggest a classification for the soils, and describe some of their properties of interest in road engineering. Newill has reported the results of laboratory tests on 158 samples of soil collected by Clare and Beaven in northern Borneo<sup>(4)</sup> and of stabilization tests on a selected number of these soils.<sup>(5)</sup> The present paper reports results of mineralogical investigations, using X-ray and differential thermal analysis methods, of 33 of these samples and another sample discussed previously<sup>(6)</sup>, and attempts to relate the mineralogy of the clay fraction of the soils to their physical properties and parent material. The mineralogical investigation extends to a different group of soils the investigations of a similar character made on a number of different types of tropical clay soils and reported previously.<sup>(6)</sup> The object of relating the mineralogy of the clay to that of the parent rock is to throw some light on the conditions under which particular types of soil develop, and thus to help engineers to learn when to expect the occurrence of similar soils elsewhere. The object of relating clay mineralogy to physical properties is to improve understanding of the way in which the behaviour of soils in roads is related to their constitution.

Soils examined

The parts of the simplified classification, used by Clare and Beaven<sup>(2)</sup>, for which representative soils were examined are as follows:-

Residual soils

- (1) Developed from igneous rocks, including volcanic material
  - (a) Acid rocks (e.g. granite)
  - (b) Intermediate rocks
  - (c) Basic rocks (e.g. basalt)
- (2) Developed from Tertiary sediments
  - (a) Yellow/red soils
  - (b) Lightly-weathered shales
  - (c) White silty and clayey soils

Transported soils

Poorly drained soils

Grey hydromorphic soils

Tables II and III, are arranged similarly, and give the location of the soils examined in the present investigation, with details of parent material, mineralogical composition, and physical properties. The physical data are quoted from Newill<sup>(4)</sup>, with additional material included.

/Mineralogical

## Mineralogical constitution of the clay fraction

The mineralogical constitution of the clay fraction was examined, using X-ray diffraction and differential thermal analysis methods. In soil mechanics the clay content is defined as the weight of those particles having an equivalent spherical diameter of less than  $2\mu$ , expressed as a percentage of the total weight. In the present investigation the mineralogical analysis was carried out on the less than  $1.4\mu$  fraction. This was to maintain consistency with the procedure of some other workers, and has the advantage of excluding some of the non-clay mineral particles which may be present in the less than  $2\mu$  fraction. It is not considered that there is likely to be a significant difference between the clay minerals present in the two fractions.

Separation of the clay fraction from the soil. The less than  $1.4\mu$  clay fraction was separated from the soil by the following procedure:-

- (1) The material passing the No. 7 B.S. sieve was treated with hydrogen peroxide to remove organic matter, as in B.S.1377. (7)
- (2) The soil was dispersed by adding sodium hexamataphosphate and agitating in a mechanical mixer, as in B.S.1377.
- (3) The clay fraction (less than  $1.4\mu$ ) was separated by sedimentation of the material passing the No. 200 B.S. sieve for 16 hours and siphoning off to a depth of 10 cm, the process being repeated several times.
- (4) After adding sufficient 0.05N hydrochloric acid to the suspension to produce an acid reaction, the clay fraction was flocculated by adding a normal solution of magnesium chloride, washed, and centrifuged to remove excess water.
- (5) The wet clay fraction was dried to equilibrium at a relative humidity of 55 per cent by placing in a vacuum desiccator over saturated magnesium nitrate solution for at least 4 days.

In order to prevent any changes in the clay minerals due to drying, such as the dehydration of hydrated halloysite, the samples had not been allowed to lose moisture from the time of sampling in the field.

## X-ray examination of the samples

In the X-ray diffraction analysis of minerals by the powder method the powdered mineral sample is placed in a beam of X-rays, which is diffracted through a limited number of angles by the crystal lattice of the sample. The X-ray diffraction pattern is recorded on a photographic film as a series of lines in the form of arcs concentric with the original X-ray beam (Fig. 1), and from the position of these lines the angles of diffraction and hence the separation or spacing of the planes of atoms producing them can be deduced. These sets of atomic spacings are characteristic of the minerals producing them. In the case of clay minerals the highest spacing observed is the most important for identification purposes; it is the distance between the sheets of atoms which are characteristic of the clay minerals, and is known as the basal spacing.

Preparation and examination of the samples. For X-ray examination, the less than  $1.4\mu$  material was examined after equilibration at 55 per cent relative humidity, and after various special pre-treatments (see Table I). The samples were examined in the form of spindles about 0.3 mm in diameter, which were prepared by mixing the suitably treated material with a little Durofix and rolling between microscope slides. X-ray powder photographs were obtained using a 114.83 mm Philips Powder Camera fitted with a special collimator and beam trap allowing low angle reflections to be recorded, and a 3-hour exposure was given using  $\text{CoK}\alpha$  radiation from a Philips PW 1009/30 X-ray diffraction generator with fine focus tube.

/Identification

Identification of individual minerals present. The characteristics used for identifying the clay minerals present are summarized in Table I, which includes details of the effect of the special pre-treatments on the basal spacing. Further details are given below, and by Brown.<sup>(8)</sup> Tables IIb and IIIb summarize the results of the X-ray examination. Only the main constituents of mixtures could be identified. The relative amounts of the different minerals present were estimated roughly from the intensity of the diffraction lines and are indicated in the tables by the scheme +++ (much), ++ (considerable), + (some), t (trace).

(a) Kaolin minerals. Minerals in this group include kaolinite, metahalloysite and hydrated halloysite. The stacking of the individual layers of kaolinite in a clay particle may be of different degrees of perfection, and kaolinites may be distinguished as ordered, partially ordered or disordered on the basis of the sharpness and other characteristics of the X-ray pattern.

In metahalloysite the stacking is more random than in disordered kaolinite, and this mineral can be distinguished from a kaolinite by the 7A line being weaker than the 4.5A line. In addition, the pattern of metahalloysite lacks the characteristic detail at lower spacings present in the kaolinite pattern, and has a more banded appearance.

Hydrated halloysite has the same structure as metahalloysite, except that there is additional water in the crystal lattice which is readily lost, e.g. by heating to 105°C. The X-ray pattern is like that of metahalloysite, except that in place of the 7A reflection there is a strong reflection at 10A, which shifts to 11A when treated with glycerol, but shifts irreversibly to 7A on heating to 105°C.

When present as a minor constituent, the particular type of kaolin mineral could often not be distinguished, in which case it has been listed in Table IIb and IIIb under kaolinite with no distinguishing symbol. Kaolinite can be distinguished in the presence of chlorite, which also gives a line at 7A, by the fact that its pattern is unaffected by hydrochloric acid treatment.

(b) Mica. Under mica in the tables are distinguished illite and muscovite, both of which have a basal spacing of 10A. The term illite is used for clay micas which are not well developed enough to give X-ray patterns characteristic of a particular mica species. In some cases the X-ray patterns were much clearer, having numerous sharp lines, and it was possible to identify muscovite as the species of mica present.

(c) Chlorite and vermiculite. Both chlorite and vermiculite have a basal spacing of 14A. In the simplest case the behaviour of these minerals to X-rays after heating at 550°C for 1 hour, is as shown in Table I. This behaviour would allow the two minerals to be distinguished. However, it is also known that for some chlorites the 14A line vanishes on heating to 550°C, while the 14A line of vermiculite can persist after heat treatment due to rapid re-hydration by atmospheric moisture. The 14A basal reflection of some vermiculites also moves to lower values on treatment with ammonium or potassium ions, but in the course of the present investigation tests on a standard sample of vermiculite (from West Chester, Pennsylvania) showed that this is not always the case. It has also been shown, for instance by Sawhney<sup>(9)</sup>, that minerals occur in soils which are intermediate between vermiculite and chlorite. In the present work the elucidation of these problems has not been attempted, but the 14A reflections have been ascribed to chlorite or vermiculite by the admittedly rather arbitrary use of the effect of heat treatment, it also being assumed that vermiculite was less affected by hydrochloric acid than chlorite.

(d) Montmorillonite. This mineral is readily distinguished by its basal spacing of 12-15A which moves to about 17.5A on treating with glycerol.

/(e)

(e) Mixed layer minerals. Sometimes layers of two types of clay mineral are interstratified in a single clay particle, giving rise to basal spacings intermediate between those of the individual clay minerals involved. Some material of this type was probably present in Sample 17.

### Differential thermal investigation of the samples

In differential thermal analysis the sample and a thermally inert reference sample are heated together in a furnace at a uniform rate. Chemical reactions (e.g. loss of water or carbon dioxide) or atomic rearrangements which occur in the sample generally involve a loss or gain of heat, which causes the sample temperature to lead or lag that of the reference sample in the region in which the reaction is taking place. The temperature difference between the sample and the reference sample is measured. The curve obtained when no thermal reactions are taking place is known as the base line. Exothermic reactions taking place in the sample give rise to peaks drawn by convention above the base line, while endothermic reactions give peaks below the base line.

Apparatus. The apparatus, which was constructed at the Road Research Laboratory and is a modified form of that described by Mitchell and Mackenzie<sup>(10)</sup>, has nickel alloy sample holders and a controlled atmosphere of nitrogen. The sample weight was 250 mg, and the reference material was calcined alumina. The sample was heated from room temperature to 1,000°C at a rate of 10°C per minute. The sample temperature and the temperature difference between sample and standard were measured with chromel-alumel thermocouples, and recorded on a single chart using a galvanometer with an optical beam followed by a split photocell driven by a servomotor, which also drove the recording pen.

Results of differential thermal investigation. A differential thermal analysis (D.T.A.) examination was made of the less than 1.4 $\mu$  fraction of the samples after equilibration at 55 per cent relative humidity. The results are discussed with the aid of the differential thermal curves for pure mineral samples obtained with the apparatus and reproduced in Figs. 2, 3 and 4. Considerable variation is reported in the curves for clay minerals occurring in soils, and this was also found in the present work. Further details are given by Mackenzie.<sup>(11)</sup>

Before discussing the results of the differential thermal investigation it will be useful to refer to the results of the X-ray examination, because X-ray analysis usually gives a more positive identification than differential thermal analysis of the clay minerals present in a sample. The X-ray examination showed that minerals of the kaolin group were present in all the soils, and that mica was also a very common mineral, while small amounts of chlorite, vermiculite or montmorillonite were often also present.

(a) Clay minerals. Kaolin minerals give a large endothermic peak on the D.T.A. curve (Fig. 2), with a maximum in the range 500-600°C which is much more prominent than the similar peaks in the 550-700°C region produced by illite (Fig. 2), montmorillonite and vermiculite (Fig. 3), and in consequence the central region of nearly every D.T.A. curve was dominated by a peak which could be ascribed to a kaolin mineral.

Illite, chlorite, vermiculite and montmorillonite show a small endothermic peak in the 800-900°C region, which may be followed by an exothermic peak. Pure well-crystallized kaolinite shows a very sharp exothermic peak at 980-1000°C, but this peak is broader, smaller, and occurs at a low temperature for less well-ordered material. The curves for most of the soils showed an exothermic peak in this region which was at a lower temperature than is usually reported for kaolinite and metahalloysite. The variations in the height and breadth of this peak, which was sometimes double, were probably due to variations in the type of kaolin mineral present, together with the effect of iron oxides and contributions from other minerals present. A small endothermic reaction sometimes seen on the low temperature side of this peak was probably due to illite, chlorite, vermiculite or montmorillonite, although sometimes reported for well-crystallized kaolinite.

At low temperatures, between 100°C and 200°C, an endothermic effect occurs in nearly all the curves. When absent, relatively well crystallized kaolinite, muscovite or possibly chlorite is indicated. A large single peak suggests hydrated halloysite, while a double peak indicates that vermiculite, montmorillonite or possibly illite may be present.

(b) Hydrated iron and aluminium oxides. The presence of goethite and gibbsite was frequently indicated by well-defined endothermic reactions in the 300-350°C region, gibbsite being observed in a number of samples in which none could be detected by X-ray analysis. Gibbsite ( $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ ) gives a peak at about 310°C, while that for goethite ( $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$ ) may be higher than 350°C for well-crystallized material, but occurs at considerably lower temperatures for less well-crystallized material. A D.T.A. curve for an artificial mixture of 15 per cent of gibbsite and 20 per cent of goethite in kaolinite is shown in Fig. 4. Below it is shown the curve obtained from the clay fraction of a soil from Sarawak (Sample 2). The percentages of gibbsite and goethite present in the soil samples were estimated by taking the differential thermal peaks to be proportional to the weight of material producing them, using the values obtained from the artificial mixture as a calibration. The results are listed in the final columns of Table IIb and IIIb. These estimates are only approximate, but it should be possible to develop the method to give more accurate results. It is seen that only small quantities of these minerals were present in the samples examined, the maximum amounts observed being 6 per cent of gibbsite and 12 per cent of goethite.

The main value of the differential thermal analyses in this investigation lay in their ability to detect and estimate the hydrated oxides of iron and aluminium present in the soils. The differential thermal curves also confirmed, although with less precision, the deductions about the clay minerals made in the X-ray examination. The limitations of the differential thermal method in this investigation were due to the soils studied containing several minerals and having rather similar compositions; kaolinite tended to dominate the curves.

#### Petrographic analyses

Petrographic analyses (and one X-ray analysis) were carried out by H.M. Geological Survey and Museum, South Kensington, on samples of the rock underlying some of the soils from Sarawak. The relevant portions of their report are quoted in Table IV. The group classification refers to the simplified classification of rocks for road engineering purposes described in Section Two of B.S. 812:1960. (12)(13)

#### Comments on the clay mineralogy in relation to soil type and parent material

The clay mineralogy of the soil can be related to the petrology of the parent material on the one hand, and to the physical properties of the soil on the other. The physical properties will be dealt with in the next section; in this section the relation between clay mineralogy and parent material will be discussed, and in addition, the effect of weathering in bringing about a progressive change in the clay mineral composition of the soil will be examined by studying the changes in composition of the soil on passing down the soil profile to less severely weathered layers.

In the classification scheme shown on page 1 the soils are divided into two main groups, the residual soils and the transported soils. The residual soils are those formed in place by the weathering of the underlying rock formation and are divided into two groups, those on igneous parent material and those on sedimentary parent material. The transported soils are those formed on material which has likewise been weathered from older rocks, but has also been moved by water and deposited in lower lying areas; only one soil in this group was examined. This classification scheme is also followed in Table II and III, a, b and c, which give the data on the soils studied. In these tables, samples from the same profile or from the same area are grouped in Groups A to H, for convenience in discussion.

/Residual

Residual soils developed on igneous rocks, including volcanic material.

Igneous rocks may be classified into three groups, acid, intermediate and basic, according to the amount of silica present. The acid igneous rocks, such as granite, have a relatively high silica content, while the basic igneous rocks, such as basalt, are low in silica.

(i) Soils on acid igneous rocks. Samples 1 and 2 were formed on granite (see Table IIa). Samples 3 and 4 will also be discussed here, because although the petrological description of their parent materials (rocks containing feldspar + glassy material, see Table IV) is not sufficient to permit their classification in the scheme acid, intermediate and basic rocks, these two soils are very similar in their clay mineral constitution to Sample 2, and in addition they come from the same area.

Leaving aside Sample 1, the remaining three soils (Group A) contain mainly disordered kaolinite (which in the case of Sample 4 is sufficiently disordered to classify as a metahalloysite), some hydrated halloysite, and also goethite and quartz (Table IIb). In addition, some material giving a 14A reflection is present, probably chlorite in Sample 2, vermiculite in Sample 3, and some of each of these minerals in Sample 4.

Sample 1 differs from the other soils developed on acid rocks in being mainly muscovite, with only a trace of kaolin mineral. This may be due to the persistence of muscovite from the parent material (a granite composed of quartz, feldspar and muscovite) while the more readily weathered biotite of the parent material of Sample 2 (a granite composed of feldspar, quartz and some hornblende and biotite) had vanished. On the other hand, in the case of Sample 1 field data indicate the possibility of the soil sample being unrelated to the underlying material, but derived from neighbouring sedimentary deposits. Its clay mineral constitution is not inconsistent with this interpretation.

(ii) Soils on intermediate and basic igneous rocks. Samples 5 and 6 (Group B) are brown soils from the Tawau area of North Borneo, formed on a Quaternary basaltic (basic) lava (Table IIIa), and are of the type on which cocoa is grown and hence are sometimes called cocoa soils. They contain kaolin mineral, hydrated halloysite and goethite but no chlorite or vermiculite (Table IIb).

Profiles C and D occurred on formations comprising Upper Tertiary intermediate and basic volcanic rocks, mainly ash (pyroclastic). Profile C shows little variation in mineralogy over the 9 ft 6 in. depth examined, comprising mainly disordered kaolinite (that in Sample 9 gave a very diffuse pattern) with some goethite (and also haematite in Sample 11). Profile D comes from the same area and formation, but from a different cutting; the underlying material was a basalt gravel, and the parent material was probably different from that of the other profile. The mineralogy of the clay fraction is also different, the minerals present being metahalloysite, montmorillonite and vermiculite, with a trace of illite and goethite.

Residual soils developed on Tertiary sedimentary rocks. Soils developed on Tertiary sedimentary rocks are classified in the scheme shown on page 1 into yellow/red soils, lightly-weathered shales, and white silty and clayey soils. The first two groups will be discussed together, because the yellow/red soils examined were found on shale, so that the lightly-weathered shales may be regarded as an intermediate stage of development between rock and more mature soils. Data on the soils examined are given in Table IIIa, b and c.

(i) Yellow/red soils and lightly-weathered shales. Profile E, from Sarawak, was developed on the Belaga formation which is mainly red shale (Table IIIa). Partially ordered kaolinite is present at all levels (Table IIIb). At the three lowest levels (15-23 ft) illite is also plentiful, but in the 10 ft specimen the proportion of illite is less, and there appears some material with higher basal spacings (at 11-12A and 14A), which went to 10A on heating and resisted HCl treatment. This material is probably of the vermiculite type, some of it interstratified with mica. In the highest

/level

level (3 ft depth) illite is absent, and a strong 14A line is present which almost vanished after HCl treatment and on heating. This material is probably mainly chlorite, with perhaps some vermiculite. Gibbsite is also present in this sample. Goethite is present at the lowest level, with a rather smaller amount at 15 ft, but none recorded for the higher levels.

Four samples from the Sarikei-Binatang Road, Sarawak (Group F), also developed on the Belaga formation, differ from the above profile in that the mica is in the form of muscovite rather than illite. Samples 21 and 22, described as soils, contain a considerable amount of disordered kaolinite in addition to the muscovite, while Samples 28 and 29, described as weathered shales, contain only a little kaolin mineral, and also some chlorite or vermiculite.

Profile G, developed on the Miri formation (much younger, and less shaly than the Belaga formation), passes from red soil at 2 and 5 ft to black weathered shale at 8, 14 and 19 ft. The clay mineral is similar throughout - mainly illite with some kaolin mineral, some chlorite or vermiculite and some montmorillonite in two of the shale levels. Sample 30, from the east coast of North Borneo, is described as a lightly weathered shale, and is similar mineralogically to profile G on the Miri formation in having much illite and some kaolin mineral, while in this case there is considerable chlorite present.

Sample 15 contained illite and kaolin mineral, with vermiculite and montmorillonite also present. The report by H.M. Geological Survey and Museum (Table IV) described the underlying material as a mudstone which swells and exfoliates in water, and contained the clay minerals illite, kaolin and chlorite (determined by X-rays). It appears that the chlorite of the deeper material may be weathering to vermiculite and montmorillonite nearer the surface.

(ii) White silty and clayey soils. The profile (H) on this class of soil (parent material unrecorded) showed a development similar to that of profile E on the Belaga formation, having illite and in this case disordered kaolinite at the lower levels, the illite giving place to chlorite or vermiculite nearer the surface, where gibbsite was also present.

Transported soils, poorly drained. Grey hydromorphic soil. The only soil in this class (Sample 34, Table II), formed on an alluvial deposit under the influence of a fluctuating water table, contained mainly illite with considerable kaolin mineral and a trace of vermiculite. Thus it was similar in mineralogy to the residual soils formed on Tertiary sedimentary deposits.

Discussion. The observations here reported showed that in broad terms a major source of differences in the clay mineralogy of soils from northern Borneo is the parent material. Soils formed on igneous rocks were found to contain predominantly kaolin minerals, vermiculite or chlorite also being present in some cases. Montmorillonite was also present in one profile. Soils formed on sedimentary rocks were characterized by the presence of illite or muscovite, which in some cases gave place to chlorite or vermiculite near the surface; kaolin minerals were also present. A transported soil was mainly illite.

These observations confirm the trends evident in earlier work on Borneo soils reported by other investigators; samples of soil on igneous rocks have been reported to contain mainly kaolin mineral<sup>(14)</sup><sup>(15)</sup>, mainly kaolin mineral and vermiculite<sup>(15)</sup> and mainly vermiculite<sup>(14)</sup>, those on<sup>(15)</sup> sedimentary rocks to contain dominant mica<sup>(14)</sup> and mica and kaolin mineral<sup>(15)</sup>, while alluvial soils have been reported to have a high clay mica content<sup>(14)</sup>.

There was in general little variation observable in the clay minerals at different depths in the soil profile, but in some profiles on sedimentary rocks illite gave place to chlorite or vermiculite near the surface. Wood and Beckett<sup>(16)</sup> have made a similar observation on a profile from Sarawak, in which they suggest that mica is weathering through chlorite to vermiculite.

/Comments

## Comments on the clay mineralogy in relation to physical properties

The physical properties of the soils (Tables IIc and IIIc) will now be related to their clay mineralogy (Tables IIb and IIIb). The plasticity data may conveniently be discussed by reference to the relative positions in which the soils lie when their plasticity indices are plotted against their liquid limits, as is done on the Casagrande classification chart (Figs. 5 and 6). On this chart, soils classified as clays are separated from those classified as silts or organic clays and silts by a line (the A-line) cutting the liquid limit axis at 20 per cent moisture content. The liquid limit axis may also be regarded as the plastic limit axis for a set of co-ordinates inclined at  $45^\circ$ , so that the plastic limit may also be read directly from the chart. For a given liquid limit, soils lying below the A-line have a higher plastic limit and a lower plasticity index than those lying above it.

In comparing the positions in which soils having different clay mineral constitutions plot on the chart, differences in the percentage of clay-sized material present have been borne in mind in the following discussion.

Residual soils on igneous rocks. Samples 5 and 6 from the Tawau area, on basaltic lava, fall well below the A-line (Group B, Fig. 5) and have liquid limits of about 105 per cent. The clay content is high, and in addition to disordered kaolinite they contain hydrated halloysite. The soils of Group A, formed on granite and glassy volcanic material, are of similar composition, also containing hydrated halloysite. They also plot below the A-line, but have lower clay contents and liquid limits. The other soil on granite (Sample 1) contains muscovite, and will be discussed below with similar soils.

Profile C, on Upper Tertiary ash, plots in a narrow band just above the A-line, with liquid limits of from 62 to 106 per cent; here the clay mineral is relatively pure disordered kaolinite. The samples of profile D, on basaltic material, were the only samples examined containing a considerable amount of montmorillonite; they plot above the A-line at liquid limits of about 120 per cent - the highest observed.

Residual soils on sedimentary rocks. Profile G (Fig. 6) on the Miri formation, which was mainly illite, plots in a band some way above the A-line, with liquid limits from 47 to 74 per cent. Profile E on the Belaga formation, containing both kaolinite and illite (giving place to vermiculite and chlorite in the upper layers), plots in a narrow band above but very close to the A-line, with liquid limits from 34 to 48 per cent. Thus the illite soils of profile G have a higher range of liquid limit and activity (0.8, 0.9) than the mixed illite and kaolinite profile E (activity 0.4 - 0.8), which is consistent with the usual experience that illite is more active than kaolinite.<sup>(17)</sup> However, the kaolinite profile C on volcanic ash has a higher range of values of the liquid limit and activity (0.5-1.8) than the illite profile G. It may be that the disordered state of the kaolinite in these soils imparts to them greater activity.

The samples of the Belaga formation having a preponderance of muscovite (Group F) plotted below the A-line, along with Sample 1, which also contained mainly muscovite. These soils also had a high silt content (62, 55, 59, 70 and 79 per cent), which is an alternative explanation of their position on the chart. Of the profile of white soils (H), Sample 31 lies close to the A-line, but Samples 32 and 33, containing only 8 per cent clay but much silt, lie well below it. The clay is illite and kaolinite, and the position of these soils on the chart may be due to their high silt contents. Sample 4 in Group A contains 64 per cent silt, and is also furthest below the A-line in its group.

## /Conclusions

## Conclusions

The clay mineralogy of 34 soils from northern Borneo has been examined, and discussed in relation to the origin of the soils and their physical properties.

Using X-ray, differential thermal and petrographic methods it was found that:-

(i) The clay mineral composition of residual soils formed on igneous rocks was mainly kaolin mineral, often with some hydrated halloysite, and sometimes vermiculite or chlorite. Goethite was also present. An exception was a soil which contained mainly muscovite, but this soil may actually have been derived from sedimentary rocks.

(ii) The soils formed on sediments differed from those formed on igneous rocks in containing a considerable amount of clay mica (illite, or less commonly muscovite), although sometimes the illite gave place to chlorite or vermiculite at the top of the profile. Kaolinite was again present, often as a major constituent, and also small proportions of chlorite or vermiculite, but hydrated halloysite was not observed.

(iii) The clay fraction of a transported soil was also mainly illite, with considerable kaolin mineral also present.

(iv) None of the soils examined contained a preponderance of montmorillonite, and a considerable amount was observed in only one profile, on basic igneous rock.

(v) In two profiles the effects of soil weathering appeared to be discernible, the illite of the lower levels giving place to chlorite or vermiculite nearer the surface.

The physical properties of the soils have been discussed in relation to their clay mineralogy by reference to the Casagrande classification chart. It was found that:

(i) the soils of the profile containing considerable montmorillonite had the highest values of the liquid limit and plasticity index,

(ii) those of the profile containing both kaolinite and illite had the lowest values, while

(iii) those of the profile containing mainly illite had intermediate values. This is as would be expected from the values for liquid limit and plasticity index usually quoted for samples of pure clay minerals. However,

(iv) the profile containing mainly kaolinite gave values tending to be higher than those for the mainly illite profile, and it was suggested that this may be due to the crystallographically disordered state of the kaolinite in this profile.

(v) Soils for which some hydrated halloysite was reported all fell below the A-line, those having the highest clay contents having a plastic limit of about 70 per cent and a liquid limit of about 105 per cent.

(vi) The soils containing muscovite also fell below the A-line, but they also had high silt contents as did two white soils having low clay contents comprising kaolinite and illite, which plotted in a similar region of the chart.

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/TABLE I

Characteristics used for identification of clay minerals in the samples studied

Mineral	Effect on the basal spacing of various pre-treatments				Notes
	Air-dry basal spacing	1 hour heat treatment		Boiling in 50 per cent HCl for 15 minutes	
		Moistened with glycerol	At 105°C		
<u>KAOLIN MINERALS</u>					
Kaolinite	7A	Unaffected	7A line vanishes	Unaffected	7A line stronger than 4.5A line. Characteristic detail at lower spacings
Metahalloysite	7A	Unaffected	7A line vanishes	Unaffected	7A line weaker than 4.5A line. Banded appearance lacking the detail of the kaolinite pattern
Hydrated halloysite	10A (at 55 per cent relative humidity)	Shifts to 11A	Shifts to 7A		Air-drying should be avoided
<u>MICA</u>					
Illite	10A	Unaffected	May sharpen		
Muscovite	10A	Unaffected			Sharper and more numerous lines than illite, with characteristic spacings
Chlorite	1 <sub>4</sub> A (second order: 7A)	Unaffected	1 <sub>4</sub> A line enhanced (7A line may still be visible)	All lines vanish	Chlorite dissolves in HCl
Vermiculite	14A	Unaffected	Shifts to about 10A		May rapidly re-hydrate after heat treatment
Montmorillonite	12-15A	Shifts to about 17.5A	Shifts to 10A		

/TABLE IIa

TABLE IIa

Residual soils on igneous rocks, and a transported soil:  
location, depth and underlying material

RESIDUAL SOILS

1. Developed on igneous rocks, including volcanic material

Group and Sample number	R.R.L. No.	Location	Depth in profile	Class of soil, and underlying material
1	1372	Sarawak: Serian-Simanggang Road. Mile 37, Quarry		(a) <u>On acid rocks</u> Granite (but the soil may be derived from adjacent sediments).
A 2	1383	Sarawak: Sebuyau Quarry		Granite
A 3	1366	Sarawak: Kuching-Serian Road, Stebun Quarry		(b) <u>On poorly crystallized volcanic materials</u>
A 4		Sarawak: Serian-Simanggang Road. Mile 3, Cutting		Same area as Nos. 1 and 2
B 5	1484	North Borneo: Apas Road Mile 25 (Quoin Hill)	9 ft	(c) <u>On intermediate and basic rocks</u>
B 6	881	North Borneo: " " Mile 24		Quaternary basaltic lava of the Tawau area
C 7	1495	North Borneo: Apas Road, Mile 8.5, Cutting	1 ft 6 in.	Upper Tertiary intermediate and basic volcanic rocks, mainly ash (pyroclastic)
C 8	1496	" " "	2 ft 6 in.	
C 9	1497	" " "	4 ft 0 in.	
C 10	1498	" " "	5 ft 6 in.	
C 11	1499	" " "	6 ft 0 in.	
C 12	1500	" " "	11 ft 0 in.	
D 13	1492	North Borneo: Apas Road Cutting	1 ft 6 in.	Underlain by gravel of decomposed basaltic rock; same formation as but different parent material from Group C
D 14	1493	" " "	3 ft 0 in.	

TRANSPORTED SOILS

Poorly drained soils

34	1435	Sarawak: Sungei Bakong Marudi, Mile 1		<u>Grey hydromorphic soils</u> Alluvial deposit
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/TABLE IIb

TABLE IIb

Residual soils on igneous rocks, and a transported soil:  
Mineralogical composition of the clay fraction

Group and Sample number	MICA M: muscovite I: illite	KAOLINITE o: ordered p: partially ordered d: disordered	HALLOYSITE M: meta-halloysite H: hydrated halloysite	C: chlorite V: vermiculite M: montmorillonite	Go: goethite Gi: gibbsite He: haematite Q: quartz	Per cent*	
						Gi	Go
1	M+++	+			Go t	2	4.5
A 2		d+++	H+	C t	Gi+ Go+ Q t	6	9
A 3		d+++	H+	V t	Go++ Q+	1	12
A 4			M+++ H+	V+ C+	Go++ Q t	2	8
B 5		d+++	H+		Go+		5.5
B 6		d+++	H+++		Go+		
-----							
C 7		d+++			Go+		
C 8		d+++			Go+		3
C 9		d+++			Go t		
C 10		d+++			Go+		
C 11		d+++			Go+He+		
C 12		d+++			Go t		
-----							
D 13	I t		M++	V++ M++	Go t		
D 14	I t		M++	V++ M++	Go t		
-----							
34	I+++	++		V t	Q+		

X-ray estimates:   +++ much  
                           ++ considerable  
                           + some  
                           t trace

\* By D.T.A.

/TABLE IIc

TABLE IIc

Residual soils on igneous rocks and a transported soil: Physical properties of the soil

Group and Sample number	Colour	Texture	Particle size distribution <sup>(1)</sup> per cent				Consistency limits <sup>(2)</sup> per cent			Activity <sup>(3)</sup>	Group <sup>(4)</sup>
			Gravel	Sand	Silt	Clay	Liquid limit	Plastic limit	Plasticity index		
1	Yellow-red-white	Silty clay	3	6	76 (79)	15 (16)	47	37	10	0.6	ML
A 2	Brown-white	Sandy clay	12	54	12 (25)	22 (46)	70	36	34	0.7	MH
A 3	Red-yellow	Sandy clay	16	34	24 (38)	26 (41)	69	43	26	0.6	MH
A 4	Brown-yellow	Silty clay	5	21	56 (64)	18 (20)	66	46	20	1.0	MH
B 5	Dark brown	Clay	0	3	10 (19)	87 (89)	103	66	37	0.4	MH
B 6	Dark brown	Clay	0	6	16 (16)	78 (80)	106	70	36	0.5	MH
C 7	Orange	Clay	0	32	27 (31)	41 (47)	64	26	38	0.8	CH
C 8	Red-yellow	Silty clay	0	28	43 (46)	29 (31)	91	35	56	1.8	CH
C 9	Grey-red	Clay	0	24	28 (30)	48 (52)	97	38	59	1.1	CH
C 10	Grey-red	Clay	0	23	17 (20)	60 (72)	62	29	33	0.5	CH
C 11	Grey-red	Clay	0	20	18 (20)	62 (69)	106	40	66	1.0	CH
C 12	Grey-red	Clay	0				104	39	65	-	CH
D 13	Orange-yellow	Clay	0	12	22 (22)	66 (67)	117	43	74	1.1	CH
D 14	Orange-yellow	Clay					121	45	76	-	CH
34	Light grey	Clay	0	8	45 (45)	47 (47)	60	29	31	0.7	CH

- (1) Numbers in brackets are for material passing No. 36 B.S. sieve  
(2) for material passing No. 36 B.S. sieve  
(3) Activity is defined as plasticity index/clay content of material passing No. 36 B.S. sieve  
(4) i.e. in Casagrande classification system

/TABLE IIIa

TABLE IIIa

Residual soils on Tertiary sediments: Location,  
depth and underlying material

RESIDUAL SOILS

## 2. Developed on Tertiary sediments

Group and Sample number	R.R.L. No.	Location	Depth in profile	Class of soil, and underlying material
15	1374	Sarawak: Serian-Simanggang Road. Mile 41.5, Cutting		(a) <u>Yellow/red soils</u> Shale
E 16	1391	Sarawak: Sarikei-Repok Road. Mile 2, Cutting	3 ft	Belaga formation (mainly red shale)
E 17	1392	" " "	10 ft	
E 18	1393	" " "	15 ft	
E 19	1394	" " "	20 ft	
E 20	1395	" " "	23 ft	
F 21	1403	Sarawak: Sarikei-Binatang Road (Kelupe)		Belaga formation
F 22	1404	" "		" "
G 23	1445	Brunei, Muara-Tutong Road, Cutting	2 ft	Miri formation (much younger and less shaly than the Belaga formation)
G 24	1446	" "	5 ft	
G 25	1447	" "	8 ft	(b) <u>Lightly-weathered shales</u> Miri formation
G 26	1448	" "	14 ft	(profile with Nos. 23 and 24)
G 27	1449	" "	19 ft	
F 28	1400	Sarawak: Sarikei-Binatang Road (Kelupe)		Belaga Formation (c.f. Nos. 21 and 22)
F 29	1402	" "		" "
30	1480	North Borneo, Labuk Road		Formation distinct from Miri and Belaga (E. coast)
H 31	1375	Sarawak: Serian-Simanggang Road. Mile 36.5, Cutting	3 ft	(c) <u>White silty and clayey soils</u> Geological origin unknown
H 32	1376	" "	8 ft	
H 33	1377	" "	12 ft	
34		(Transported soil - see Table Ia)		

/TABLE IIIb

TABLE IIIb

Residual soils on Tertiary sediments:  
Mineralogical composition of the clay fraction

Group and Sample number	MICA M: muscovite I: illite	KAOLINITE o: ordered p: partially ordered d: disordered	HALLOYSITE M: meta-halloysite H: hydrated halloysite	C: chlorite V: vermiculite M: montmorillonite	Go: goethite Gi: gibbsite He: haematite Q: quartz	Per cent*	
						Gi	Go
15	I+	+		V+ M+	Go t		
E 16		p+++		C++		2.5	
E 17	I++	p+++		V+, with some interstratification			
E 18	I+++	p+++			Go+		4
E 19	I+++	p+++					
E 20	I+++	p+++			Go+	1.5	3
F 21	M+++	d++					
F 22	M+++	d++					
G 23	I+++	+		V+	Q t		
G 24	I+++	+		V t or C t	Q t		
G 25	I+++	+		C+ M+	Q t		
G 26	I+++	+		C t or V t	Q t		
G 27	I+++	+		C+ M+	Q t		
F 28	M+++	+		V t			
F 29	M+++	t		C++			
30	I+++	+		C++			
H 31		d+++		C+ or V +	Gi+	4	
H 32	I++	d+++			Gi t	0.5	
H 33	I++	d+++					

X-ray estimates: +++ much  
++ considerable  
+ some  
t trace

\* By D.T.A.

/TABLE III.

TABLE IIIc

Residual soils on Tertiary sediments: Physical properties of the soils

Group and Sample number	Colour	Texture	Particle size distribution <sup>(1)</sup> per cent				Consistency limits <sup>(2)</sup> per cent			Activity <sup>(3)</sup>	Group <sup>(4)</sup>
			Gravel	Sand	Silt	Clay	Liquid limit	Plastic limit	Plasticity index		
15	Yellow-brown	Clay	4	13	35 (40)	48 (55)	74	33	41	0.8	CH
E 16	Brown	Sandy clay	0	39	35 (36)	26 (27)	34	22	12	0.4	CL
E 17	Red-white	Silty clay	0	29	36 (37)	35 (36)	48	26	22	0.6	CI
E 18	Red-white	Sandy clay	1	48	31 (37)	20 (24)	39	24	15	0.6	CI
E 19	Pink-white	Silty clay	0	34	40 (41)	26 (27)	38	24	14	0.5	CI
E 20	Brown	Silty clay	0	39	45 (45)	16 (16)	35	23	12	0.8	CI
F 21	Orange-white	Silty clay	0	0	62 (62)	38 (38)	72	41	31	0.8	MH
F 22	Yellow-white	Silty clay	0	11	54 (55)	35 (35)	45	33	12	0.3	MI
G 23	Red	Clay					74	29	45	-	CH
G 24	Red-grey	Clay					74	28	46	-	CH
G 25	Black	Weathered shale	0	18	46 (47)	36 (37)	64	21	43	-	CH
G 26	Black	Weathered shale	0	12	56 (57)	32 (32)	50	20	30	0.8	CI
G 27	Black	Weathered shale	0	12	56 (57)	32 (32)	47	18	29	0.9	CI
F 28	Red	Weathered shale	(5) 0	24	55	21	61	42	19	0.8	MH
			(6) 0	3	74	23	-			0.8	
F 29	Grey	Weathered shale	(5) 0	18	67	15	43	28	15	0.9	MI
			(6) 0	1	79	20	-			0.8	
30	Black	Weathered shale									
H 31	White	Silty clay	0	30	50 (52)	20 (21)	50	29	21	1.0	MI
H 32	White	Silty clay	0	30	62 (64)	8 (8)	53	38	15	1.9	MH
H 33	White	Silty clay	0	32	60 (62)	8 (8)	56	40	16	2.0	MH

(1) (2) (3) (4) see Table IIc

(5) Standard treatment

(6) Dispersion treatment repeated

/TABLE IV

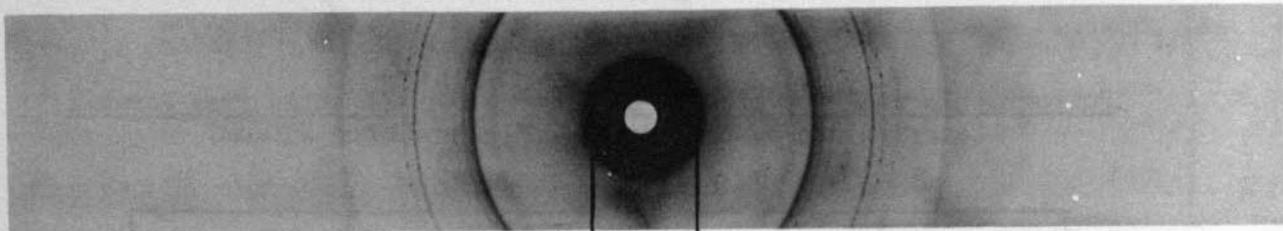
TABLE IV

Petrographic analyses of rock underlying certain soils from Sarawak  
 (carried out by H.M. Geological Survey and Museum)

Soil Sample number	Description of underlying rock
1	A medium-grained granite composed of quartz, alkali feldspar, albitic oligoclase and patches of muscovite. Some of the feldspar is carbonated and sericitized.- Granite group.
2	A biotite-hornblende granodiorite. It is composed of subhedra of oligoclase, interstitial quartz and subordinate amounts of green hornblende and biotite. - Granite group.
3	A crystal-vitric tuff which consists of numerous glass shards, fragmental quartz and feldspar and granules of carbonate in a brown glassy isotropic groundmass.
4	A trachytic pitchstone which consists of subparallel microliths of feldspar and minute weakly birefringent granules in a green glassy matrix.
15	A pale grey mudstone which swells in water and 'exfoliates'.  Summary of X-ray analysis: the clay contains appreciable amounts of chlorite, illite, kaolin and quartz, but it is not possible to indicate the relative proportions in which these constituents are present.

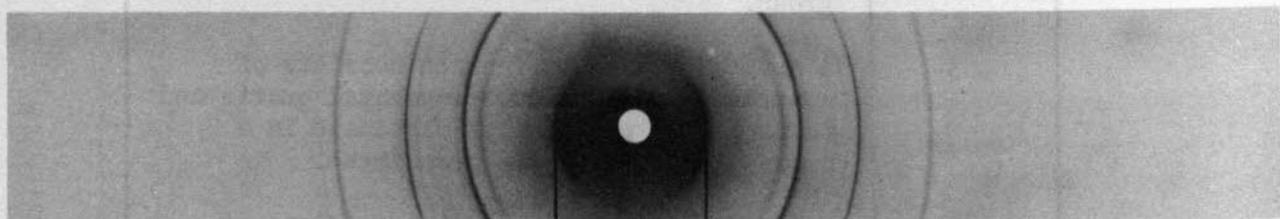
Road Research Laboratory,  
 February, 1963.  
 BK.

MONTMORILLONITE



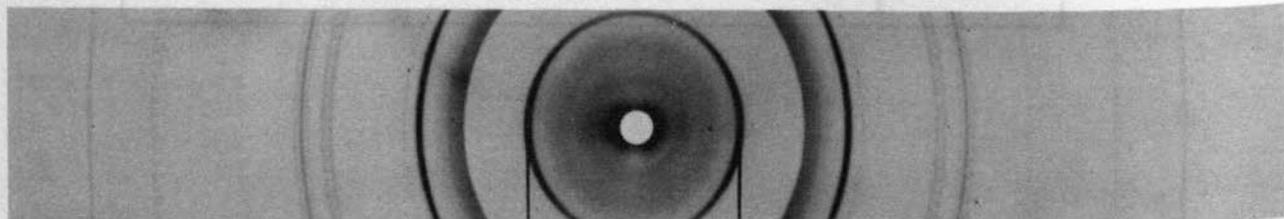
Diffraction ring corresponding to a spacing of 14 Ångström Units between layers of atoms in the clay crystal. (Expands to 17 Ångström Units on moistening with glycerol)

ILLITE



10 Ångström Units spacing

KAOLINITE



7 Ångström Units spacing

Fig.1. X-RAY DIFFRACTION ANALYSIS—CHARACTERISTIC X-RAY PATTERNS OF COMMON CLAY MINERALS

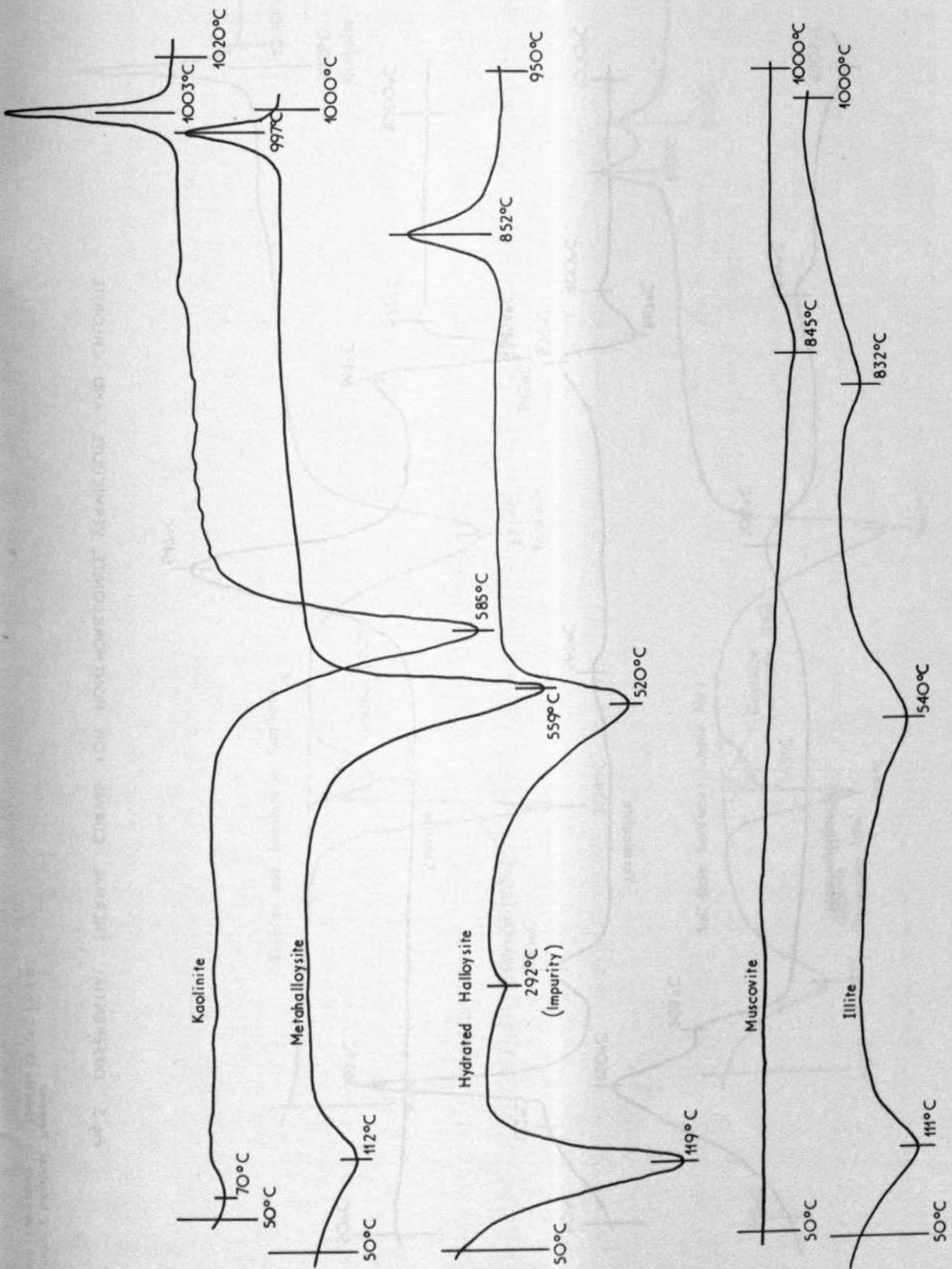


Fig. 2. DIFFERENTIAL THERMAL CURVES FOR KAOLIN AND MICA MINERALS

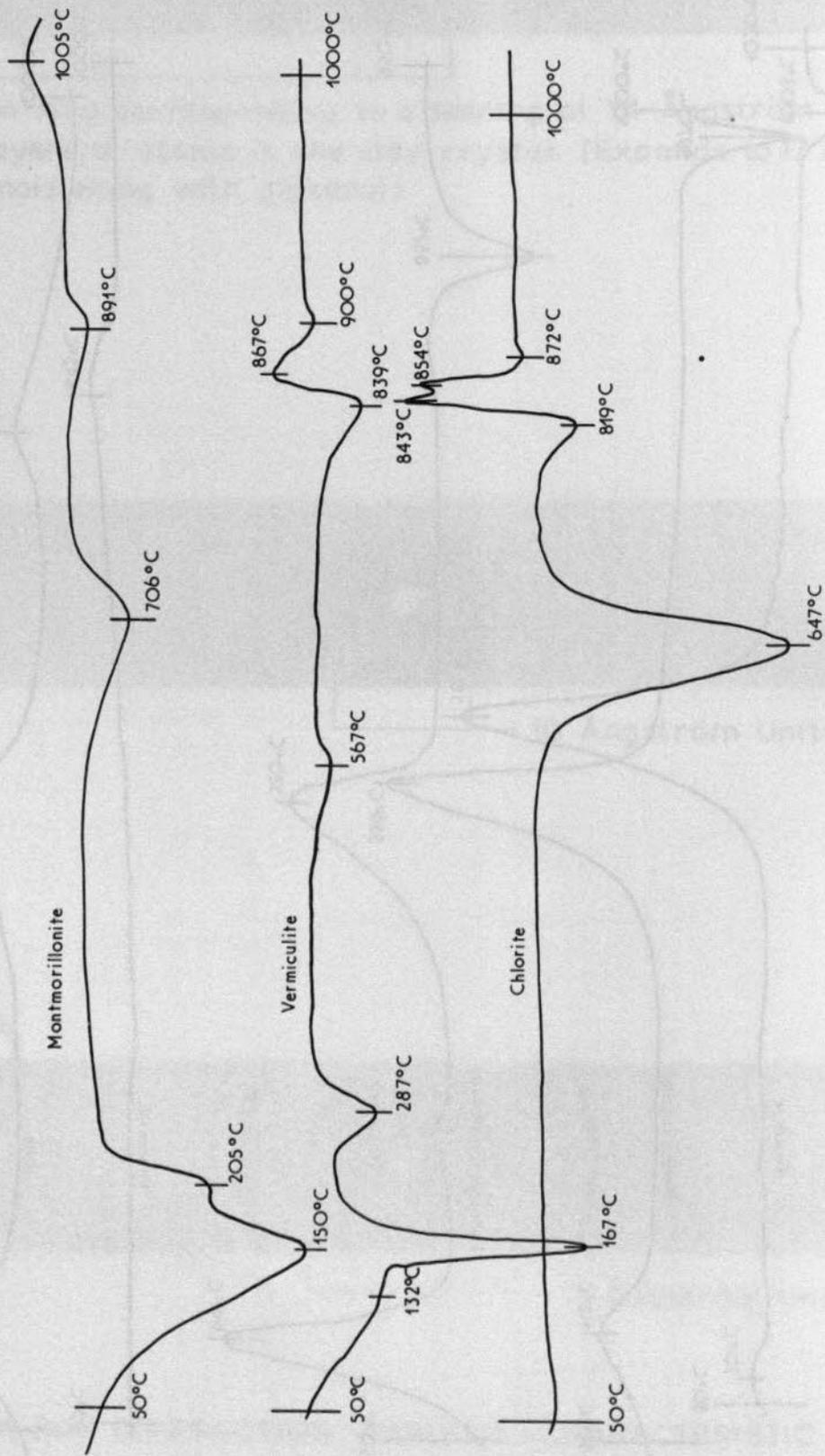


Fig. 3. DIFFERENTIAL THERMAL CURVES FOR MONTMORILLONITE, VERMICULITE AND CHLORITE

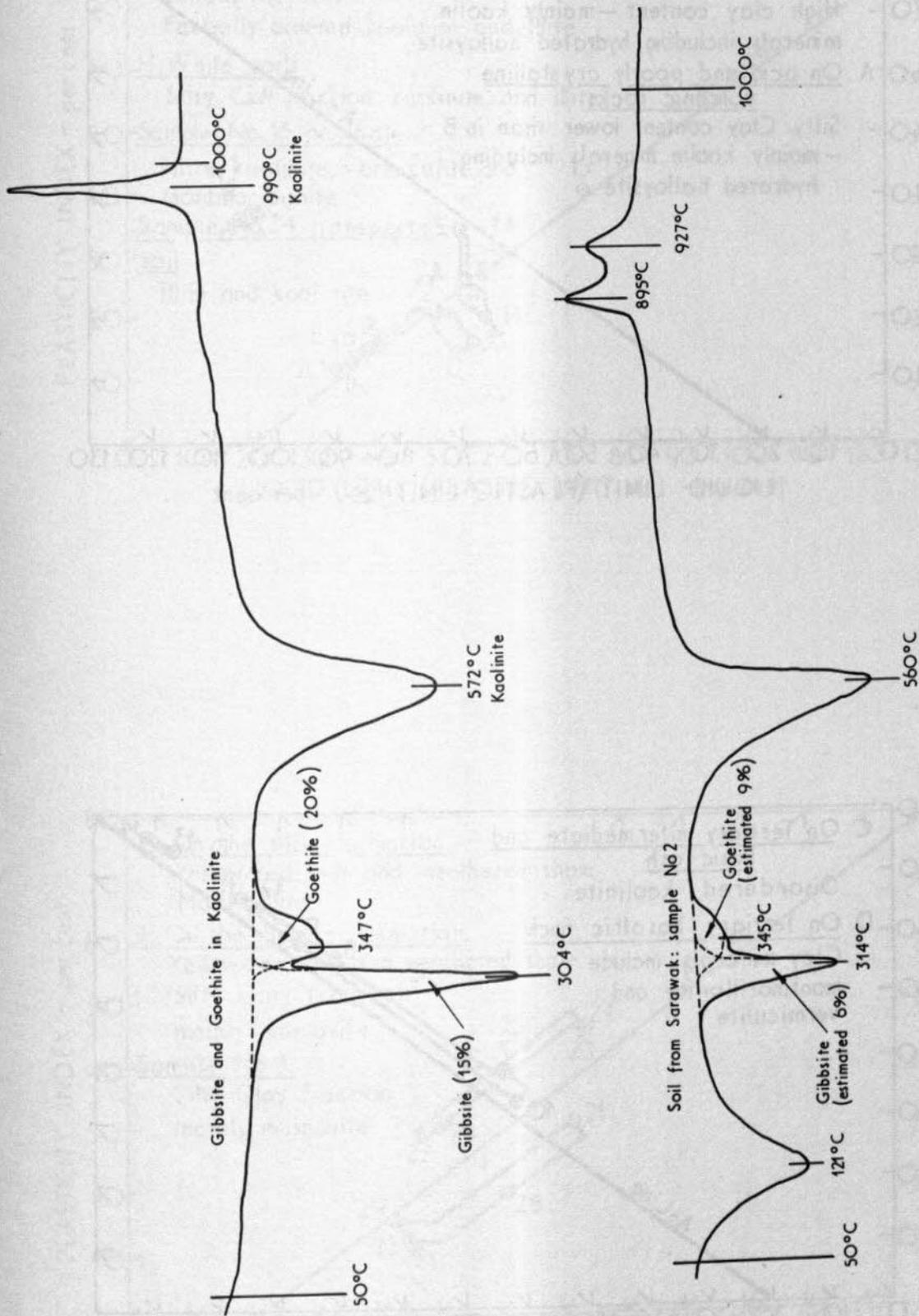


Fig. 4. DIFFERENTIAL THERMAL CURVES FOR MATERIAL CONTAINING GIBBSITE AND GOETHITE

# SOILS ON IGNEOUS ROCKS

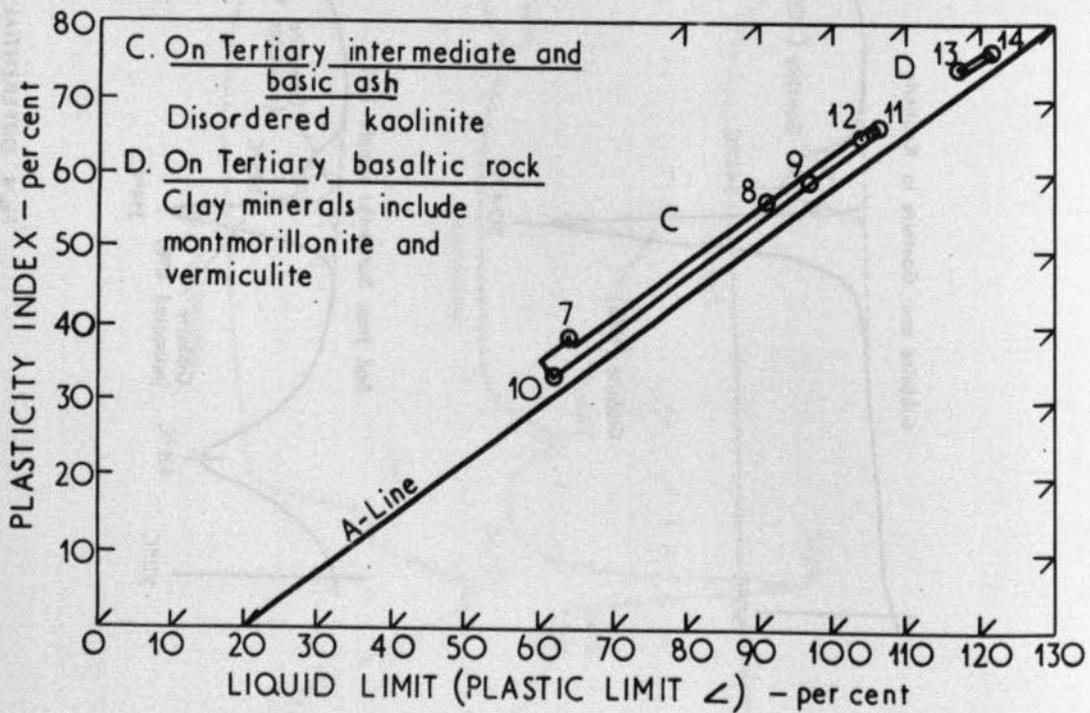
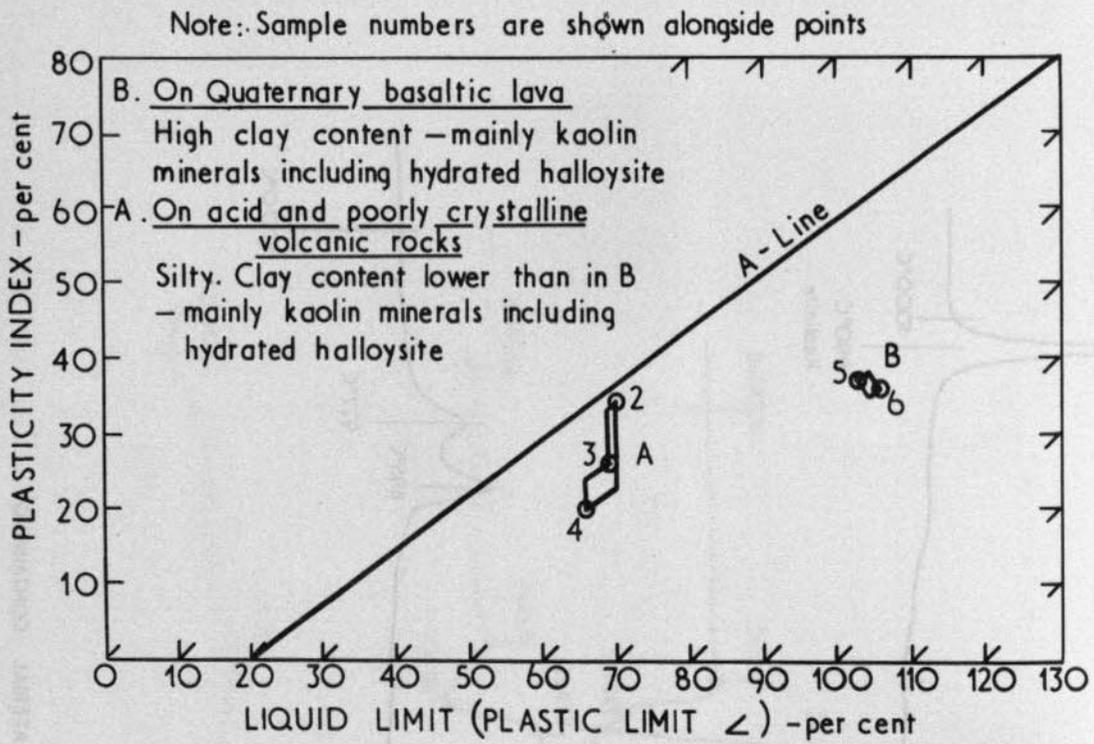


Fig. 5. PLASTICITY CHARTS FOR RESIDUAL SOILS DEVELOPED ON IGNEOUS ROCKS

SOILS ON SEDIMENTARY ROCKS

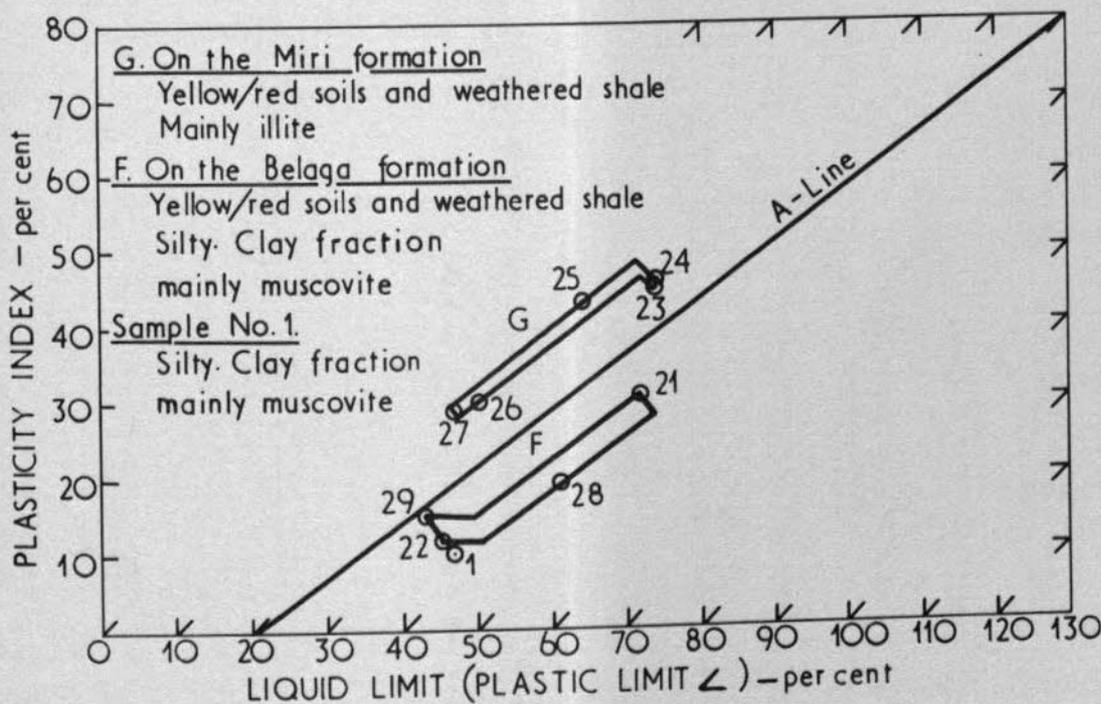
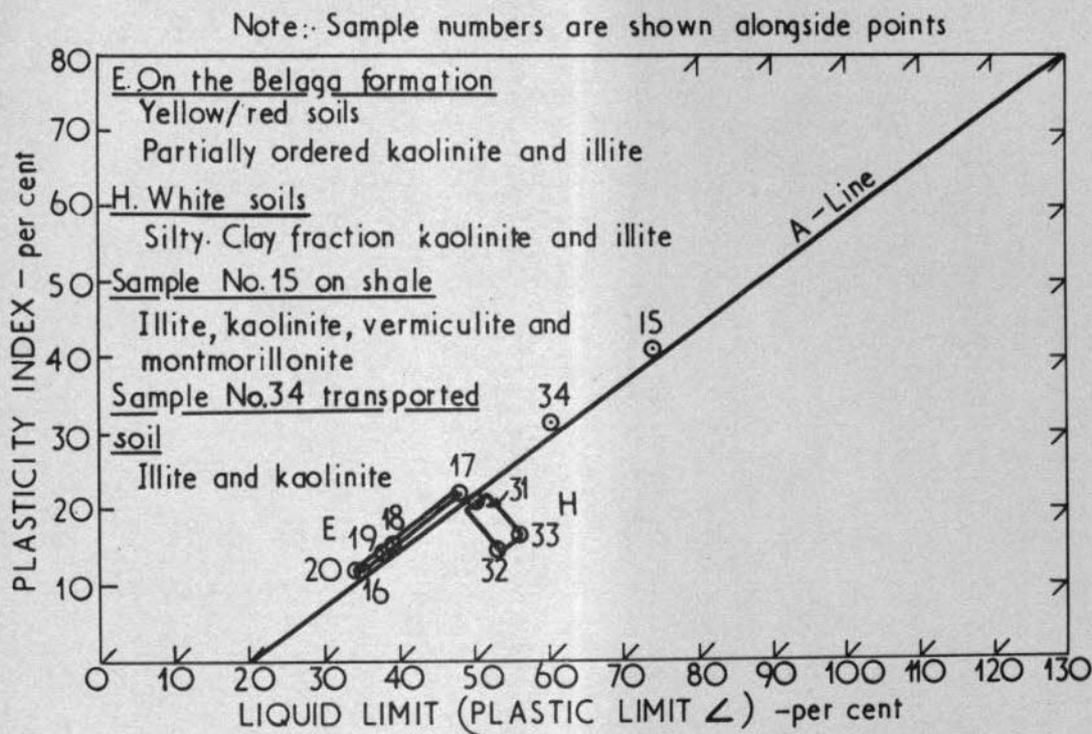


Fig.6. PLASTICITY CHARTS FOR RESIDUAL SOILS DEVELOPED ON SEDIMENTARY ROCKS, AND SAMPLES No.1 AND No.34

