# MINERALOGY AND FABRIC CHARACTERIZATION AND CLASSIFICATION OF WEATHERED GRANITIC ROCKS IN HONG KONG

GEO REPORT No. 41

T.Y. Irfan

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CIVIL ENGINEERING DEPARTMENT
HONG KONG

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## PREFACE

In keeping with our policy of releasing information of general technical interest, we make available some of our internal reports in a series of publications termed the GEO Report series. The reports in this series, of which this is one, are selected from a wide range of reports produced by the staff of the Office and our consultants.

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The Geotechnical Engineering Office also publishes guidance documents and presents the results of research work of general interest in GEO Publications. These publications and the GEO Reports may be obtained from the Government's Information Services Department. Information on how to purchase these publications is given on the last page of this report.

AWMalone

A.W. Malone
Principal Government Geotechnical Engineer
February 1996

## FOREWORD

The behaviour and engineering properties of weathered rocks are controlled by the mineralogy and fabric characteristics of the rock material as well as the discontinuities within the rock mass. In the saprolites and residual soil, the influences of discontinuities are greatly reduced and the mineralogy, grain size, microfabric and the bonding characteristics (i.e. soil microstructure) become more dominant in controlling engineering properties and in-situ behaviour. To date, these properties have not been well documented for weathered rocks and soils in Hong Kong.

As part of its research and development programme, the Geotechnical Engineering Office has been looking into ways of determining and characterising the mineralogical and fabric properties of weathered rocks, in particular the soil grades, with the objective of understanding their behaviour in the laboratory and in the field. This document summarizes the study results on the mineralogical and fabric properties of the weathered granitic rocks within the context of a revised material and mass weathering classification scheme and makes particular reference to the effects of their specific mineralogy and microstructure on the soil classification and index properties and behaviour.

The results of this study have already been used by the GEO in drafting local standards for soil classification and index tests based on BS 1377:1990 version (see Chen, 1993).

Some of the laboratory analyses reported here were carried out by Dr. S. R. Hencher and Dr. E. J. Ebuk at Leeds University under a GEO research consultancy, and by Dr. O. A. Awoleye (under supervision of Dr. P. Smart) at Glasgow University as part of his post-graduate research, as well as by Dr. L. R. Dobereiner at LCPC in Paris, on samples provided by the GEO under no-charge scientific collaborations. Their contributions to the study are acknowledged.

The report has been written by Dr. T. Y. Irfan who also initiated the study and carried out most of the in-house mineralogical and fabric analyses, coordinated and arranged for testing at overseas institutions and commercial laboratories.

Dr. I. Basham, Dr. R. Shaw and Dr R. P. Martin reviewed the draft document. Dr. Basham made useful comments on an earlier draft, in particular on the mineralogical aspects of the study, which have been incorporated into the final report. Acknowledgements are also due to Mr. K. S. Wong and the Special Projects Division technical staff who provided assistance with field sampling and transport of samples to overseas laboratories.

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## 1. INTRODUCTION

The engineering properties of a rock mass are a function of the physical properties of the rock material together with the effects of the discontinuities within the mass and the pore fluids within both the discontinuities and the material. The properties of the rock material are controlled by the mineral composition, texture (grain size and shape), fabric (arrangement of minerals and voids), and the weathering state. In the soil range of an intensely weathered rock, the influences of discontinuities are greatly reduced and it is the mineralogy, grain size, microfabric and the remnant or secondary bonding characteristics (collectively known as the soil microstructure) which control its engineering properties and insitu behaviour.

The mineralogical and textural aspects of weathered igneous and other rocks in Hong Kong are poorly documented in the published literature. These aspects are well-studied in some countries having similar rock formations, particularly in the case of granites. To date, little attempt has been made in Hong Kong to relate the engineering properties and behaviour of weathered rocks and the soils formed from them to their basic mineralogical and textural characteristics. It should be born in mind that the characterization of these properties for engineering purposes is not easy because of great variability and inhomogeneity shown, particularly by the igneous rocks, as a legacy of their geological and weathering history.

As part of its research and development programme, the Geotechnical Engineering Office (GEO) has been looking into ways of determining and characterizing the petrographical properties of weathered rocks and soils in order to make a better assessment of their laboratory and insitu properties and behaviour. This was done through a number of in-house geotechnical projects and research work together with external research consultancies (e.g. on shear strength) where the mineralogical and fabric properties of the sampled materials were also determined. In addition, a small number of petrographical studies was undertaken by overseas researchers as part of post-graduate or post-doctoral research on the samples provided by the GEO under no-charge scientific collaborations. Limited additional mineralogical and fabric analyses were also carried out in-house on some weathered rock specimens in order to supplement the data already compiled and to put the results in a structured framework in terms of rock type and weathering state.

This document outlines the petrographical and other methods applied to characterize the mineralogical and fabric properties of the weathered granitic rock material and gives a synthesis of the results of the chemical, mineralogical and fabric analyses carried out. It also describes the typical physical, chemical and mineralogical changes occurring in the rock material caused by weathering and other alteration processes and establishes a model for granite weathering. Although the study concentrated on the changes occurring in granites at the material scale, engineering geological descriptions of the sampling sites and the general characteristics of the weathering profiles in granites and other igneous rocks in Hong Kong are also given to place these material characteristics in the perspective of rock mass behaviour. In this context, a brief review of the engineering classification schemes including a recently proposed soil mechanics scheme adopted to describe the weathered igneous rocks in Hong Kong, is also given. The effects of hydrothermal alteration, which is considered to be important in some Hong Kong granites and the rocks they have intruded, are also discussed. The engineering properties of weathered granites are not discussed here but a brief reference is made to the effects of specific mineralogy and microstructure developed in the saprolitic and residual soils on the results of soil classification tests.

## 2. GEOLOGICAL SETTING OF IGNEOUS ROCKS IN HONG KONG

### 2.1 General

Granites, granodiorites and associated volcanic rocks of Mesozoic age underlie a greater part of the Territory of Hong Kong including the main urban area around Victoria Harbour (Figure 1). The volcanic rocks, several thousand metres thick, were formed mainly in the Middle to Upper Jurassic and have been intruded by a number of granitic plutons of Upper Jurassic to Lower Cretaceous age (Strange & Shaw, 1986; Strange, 1990). The volcanic and intrusive activity took place during the Yenshanian Orogeny which also affected large parts of Southeast China (Allen & Stephens, 1971).

### 2.2 Granites and Granodiorite

The granites occur as a series of high level elliptical or circular-shaped plutons, ranging from 5 to 20 km in diameter (Strange, 1990). They display cross-cutting intrusive relationships, indicating that they are of slightly different ages. In places, there is evidence of modification and alteration of an older granite by a subsequent intrusion. Within each pluton, the rock displays broadly distinctive textural and petrological characteristics, but variations of fabric and mineralogy can occur even in small specimens, in addition to changes brought about by late stage magnatic modifications and hydrothermal alteration. The pluton outcropping in the urban areas of Kowloon and northern Hong Kong Island has been dated as 138 ∓ 1 million years (Sewell et al, 1992).

Geochemical analyses indicate distinctive differences in chemical composition among plutons. For example, the CaO content varies from about 1.5% to 2.1% in the coarse-grained granites of the Sung Kong pluton to 0.9% to 1.3% in the Kowloon pluton and 0.5% in the fine-grained granite of the Mount Butler pluton (Table 1).

In the recent mapping of the Territory, granites have been classified into four main types according to grain size (Strange, 1990):

| Granite Type | Grain Size |
|---|---|
| Fine-grained Granite | 0.06 to 2 mm |
| Fine-to-Medium-grained Granite | About 2 mm |
| Medium-grained Granite | 2 to 6 mm |
| Coarse-grained Granite | 6 to 20 mm |

Granitic rocks with a grain size of less than 0.06 mm have been classified as rhyolite, usually occurring in dyke form, although the term 'aplite' has been retained to describe light coloured, uniform-grained granitic dykes. The textural terms such as 'megacrystic', 'equigranular' and 'inequigranular' are also used as secondary qualifiers for the full description of the granite types.

Granodiorite is a plagioclase-rich rock of the granitoid family, with the plagioclase/alkali feldspar ratio in excess of 65% of the total feldspar content, but quartz content similar to the granites. It contains a higher amount of iron-magnesium rich dark minerals (e.g. biotite and hornblende), usually in excess of 10%.

## 2.3 Other Igneous Rocks

Small plutonic bodies and dykes of quartz-syenite and quartz-monzonite occur throughout the Territory, usually intruding the granites. These are silica-deficient igneous rocks with a quartz content less than 20%. They typically display megacrystic textures with large feldspars aligned sub-parallel to one another.

Dykes are present throughout the Territory. They range from acidic and intermediate (dacite, andesite) composition, associated with Upper Jurassic intrusive activity, to basic composition (basalts, lamprophyres and gabbros), of presumed Tertiary age, and vary in thickness from a few centimetres to a couple of hundred metres.

## 2.4 Late-Stage Alteration and Metamorphism

In addition to modification (metasomatism) of the older granites by the younger plutons, which usually results in an inequigranular texture, the granitic rocks show evidence of hydrothermal alteration by late-stage magmatic fluids, producing kaolinization and greisenization (mica enrichment). Locally, alteration has been very extensive. For example, about 100 m thickness of a fine-grained granite in the Rennie's Mill area has been greisenized by late-stage hydrothermal fluids (Strange & Shaw, 1986). A more detailed account of hydrothermal alteration is given in Section 3.

In the Lo Wu-Tuen Mun area, the low to medium-grade regional metamorphism associated with overthrusting of Palaeozoic basement onto Jurassic volcanic rocks also affected the granitic rocks, resulting in mylonitization and formation of a schistosity in the rock (Langford et al, 1989).

## 2.5 Structure

### 2.5.1 Faults and Folds

Both granites and volcanic rocks are affected by faulting dating back to the late Palaeozoic. The most dominant and persistent fault directions are NE-SW and NW-SE (Burnett & Lai, 1985). The NW-SE trending faults are known to be younger in age since they displace the NE-SW trending faults. The major faults have crush zones with quartz veins, varying from 0.1 m to 30 m wide. McFeat-Smith et al (1985) reported that the average spacing of minor faults and fracture zones in the New Territories is about 15 to 25 m.

In the vicinity of the fault zones, especially those earlier fractures which were formed during cooling of the magma, the rock often shows evidence of hydrothermal alteration and minor mineralization (Choy et al, 1987).

Some large-scale gentle and open folding has been recognised in volcanic rocks overlying granitic plutons. These are at least in part related to the rise of the underlying granitic batholiths into a relatively competent volcanic cover.

### 2.5.2 Jointing

Usually four or five, generally clearly defined, major sets of joints are found in the granitic rocks at any one locality in Hong Kong. Generally, one set comprises gently-dipping exfoliation (sheeting) joints, although some of them may also be primary cooling joints. These joints have varying dip directions, usually sub-parallel or parallel to the ground surface, and very rough undulating surfaces. Most joints at a site are subvertical to vertical. These are tectonic joints, but many may also be primary cooling joints. Minor sets or random joints having steep dips (40° to 70°) may also occur.

The mean trends of various joint sets may vary from one location to the other, related to regional and local stresses during tectonism, the cooling history of each pluton and the weathering and erosional history.

The joint spacing is usually greater in the medium- and coarse-grained granites, 0.5 m to over 3.0 m, than in the finer grained equivalents, 0.2 m to 0.6 m. However, the mean joint spacing and also the spacing of individual sets may vary from one locality to another, being smaller in the vicinity of faults and fault zones. The spacing of the gently-dipping to flat-lying joint set usually decreases towards the higher levels in a site.

## 2.6 Geomorphology

The present geomorphology of the Territory reflects a complex history of weathering, erosion and depositional changes in response to climatic variation and sea-level fluctuations which took place in the late Tertiary to Quaternary. The onshore topography has been strongly influenced by the major geological units and the regional structure. Bennett (1984), citing Chinese sources, stated that the present topography was more or less initiated by the late Pliocene, over 3 million years ago. A major transgression in the Holocene, about 8 000 years ago, resulted in drowning of the lower reaches of the mountains. The lower and middle slopes of the larger hills are covered by thick deposits of mass-wasting materials, generally known as colluvium, dating back to at least the early Pleistocene, about 130 000 to 700 000 years ago (Lai & Taylor, 1986).

Volcanic rocks, especially the fine-grained tuffs, generally form the highest sharper peaks with deeply dissected side slopes in the hilly terrain of Hong Kong. Rock outcrops are common on the upper slopes. The lower slopes are covered by a relatively thin zone of weathered rock and often colluvium.

Granites generally form the lower, more rounded and deeply weathered hills. The drainage pattern is often dictated by major tectonic discontinuities. Rock outcrops are rare except along drainage lines and deep cuttings, apart from local occurrences of large boulders and corestones on the surface. The fine-grained granites are generally more resistant to weathering than the coarse-grained varieties. The gently rolling hill and valley topography of the granites has been greatly modified in the urban areas by the intense construction activity.

In some cases, there is a strong structural control of the terrain by the faults. For example, the major drainage lines in the eastern part of Hong Kong island follow NE and NW trending faults. The faults have also dictated the pattern of weathering profiles (Section 3).

# 3. WEATHERING AND ALTERATION

## 3.1 General

Weathering is the process of alteration of rocks and soils at or near the earth's surface by physical, chemical and biological processes under the direct influence of the hydrosphere and atmosphere. Water is the most important weathering agent as it affects the initiation of chemical reactions and temperature is important in controlling the rate of these reactions.

Weathering occurs in all types of climatic environment but to a different intensity. The major factors which control the rate and type of weathering and the depth to which it extends are :

climate
topography
rock type (mineralogy, grain size, etc)
discontinuity state and structure characteristics
groundwater
time
organisms

Weathering processes can be grouped into three broad categories; physical or mechanical weathering (disintegration), chemical weathering (decomposition) and biological weathering. Generally all three processes act simultaneously. Chemical weathering is dominant in warm and humid tropical climates.

Only a brief review of the more important weathering processes is given in this chapter, together with a summary of the main mineralogical changes occurring in the silicate minerals, which are the major constituents of acidic igneous rocks. This is considered important in understanding the mineralogical and fabric changes taking place in the granitic rocks described in later chapters. Extensive reviews of weathering processes and the resultant mineralogical, chemical and physical changes which take place in various minerals and rocks are given, for example, by Loughnan (1969) on chemical weathering of silicate minerals, Ollier (1975) on weathering in general, Gidigasu (1975) on lateritic soils in tropical regions, Chesworth (1977) on igneous rocks, Berner & Holdren (1977) on feldspar weathering, and Dearman et al (1978) and Irfan & Dearman (1978a) on granites.

## 3.2 Weathering Processes

### 3.2.1 Physical Weathering

Physical weathering is the mechanical breakdown of minerals and rocks by mechanical processes such as wetting and drying and diurnal temperature changes. Physical breakdown is also an intrinsic feature of the effects of chemical weathering.

The most common physical weathering processes are summarized in Table 2. Physical weathering results in the opening up of discontinuities, the formation of new discontinuities by rock fracture and the opening of grain boundaries and fractures in individual mineral grains. Significant physical weathering may occur over relatively short periods, whereas chemical processes require much longer periods before the effects can be observed. Two of the most important physical processes which contribute to the general weathering of rocks in Hong Kong are exfoliation (sheeting) and wetting and drying.

Sheeting. Sheeting is a common phenomenon in granites in Hong Kong but also occurs in other massive rocks including tuffs. The sheeting joints can be very major structures extending for many metres. Although they develop more or less parallel to the ground surface, some sheeting joints are found to be at steep angles to the present day surface. These are fossil structures and reflect the past ground surface.

Slaking. Rocks can disintegrate when subjected to repeated wetting and drying. The disintegration process may be rapid in weakly-cemented sedimentary rocks and also in moderately to highly decomposed granitic and volcanic rocks. Repeated shrinkage and swelling due to drying and wetting set up internal pressures in rocks which can eventually lead to complete disintegration.

The slaking process can be significant in geotechnical engineering. Inaccurate description and determination of properties may result if logging and testing are carried out after a significant deterioration has taken place.

### 3.2.2 Chemical Weathering

Minerals formed at high temperatures and pressures are unstable at the low temperature and pressure conditions prevailing at or near the earth's surface. They change chemically into mineral forms that are more stable. The type of secondary minerals produced and the rate of the associated chemical reactions depend on many factors. One factor, which is particularly important in determining the course of weathering and the type of secondary mineral formed, is the removal of weathering products from the system. For example, kaolin minerals and gibbsite will form from feldspars if continued removal of cations occurs under intense flushing conditions, such as those found on most hillsides and hilltops in Hong Kong. Cation-rich clay minerals such as montmorillonite and illite will form where released cations are retained within the weathering zone.

The influence of parent rock may be negligible under intense chemical weathering conditions. Kaolinite and montmorillonite-rich soils can form from the same parent rock under different climatic conditions, topography and time. In some cases, mixed layer mineral assemblages may occur, even to the extent that entirely different clay minerals such as kaolinite and montmorillonite may be stacked together.

The most common chemical processes are summarized in Table 2. The two most important chemical processes operating in the humid environment of Hong Kong are hydrolysis and solution. The principal chemical re-agent in these processes is water. The pH (concentration of H+ ions), Eh (redox potential for oxidation and reduction), ionic potential and the presence of organic matter are also very important.

Hydrolysis. Hydrolysis is acknowledged to be the most common process in the chemical breakdown of common silicate and aluminosilicate minerals (e.g. feldspars) to clay minerals. The following formula shows how either kaolinite or montmorillonite is formed from weathering of plagioclase feldspars by hydrolysis, depending on the hydrogen ion concentration :

$$\underset{\text{(Albite)}}{2NaAlSi_3O_8} + \underset{\text{(aq.)}}{2H^+} + 9H_2O \rightarrow \underset{\text{(Kaolinite)}}{H_4Al_2Si_2O_9} + \underset{\text{(aq.)}}{4H_4SiO_4} + \underset{\text{(aq.)}}{2Na^+}$$

$$\underset{\text{(Albite)}}{8NaAlSi_3O_8} + \underset{\text{(aq.)}}{6H^+} + 28H_2O \rightarrow \underset{\text{(Montmorillonite)}}{3Na_{0.66}Al_{2.66}Si_{3.33}O_{10}(OH)_2} + \underset{\text{(aq.)}}{14H_4SiO_4} + \underset{\text{(aq.)}}{6Na^+}$$

Solution. Solution is a process which affects not only rocks composed of soluble minerals such as $CaCO_3$ and NaCl but also feldspar-bearing rocks. For example, Baynes & Dearman (1978a) reported formation of etch pits and solution along cleavage planes and grain boundaries of feldspars in early stages of weathering of granites. Irfan (1988) suggested that the rapid increase in porosity of alkali feldspars in a completely weathered granite from a well-drained hilltop on Hong Kong Island might result from extensive etch-pit solution of feldspars without forming clay minerals at a very late stage of weathering. Scanning electron microscope studies by Glasgow University (Awoleye, 1991) on samples from the same site confirmed rapid solution of alkali feldspars (Section 10).

The amount of solution depends on the amount of water passing the surface of a particle and the solubility of all the solids being dissolved. Even quartz is slightly soluble at all pH values, with a drastic increase in solubility above a pH of 9. Amorphous silica is nearly 20 times as soluble as quartz (Selby, 1982).

Oxidation and Reduction. Oxidation in the context of weathering is the reaction with oxygen to form oxides (e.g. hematite and limonite). If water is present then oxyhydroxides (e.g. goethite) are formed. Oxidation is an important process in weathering of iron-bearing minerals such as biotite commonly found in Hong Kong granites. Iron as $Fe^{2+}$ is oxidized to $Fe^{3+}$ if in contact with oxygenated waters. The iron-oxides being typically yellowish brown to reddish in colour stain the rocks along joints and other fractures, sometimes to great depths.

Reduction is the reverse of oxidation and involves the release of oxygen from iron-oxides in mainly water-logged sites, mostly by the action of anaerobic bacteria. Reduction produces grey and green colours in contrast to red and yellow colours produced by oxidation. Alternate oxidation and reduction of iron can be produced in seasonally fluctuating groundwater environments such as Hong Kong and the soil becomes mottled yellowish grey and reddish brown where reduced iron is oxidized.

## 3.3 Decomposition of Minerals in Acidic Igneous Rocks

The major primary minerals occurring in granites and volcanic rocks of acidic composition are plagioclase and alkali feldspars and quartz with some biotite and minor muscovite. Minor amounts of more basic minerals (e.g. hornblende) occur in the more intermediate igneous rocks such as granodiorite. In the quartz-syenites, feldspars are more dominant with a small amount of quartz.

Quartz and muscovite are the most stable minerals in these rocks followed by alkali feldspars and biotite. The plagioclase feldspars are the least resistant to chemical alteration. It is usually the plagioclase feldspars which start decomposing at very early stages of weathering, probably accompanied or preceded by the alteration of biotite and hornblende (if any). A number of types of secondary minerals can be formed from each mineral depending on the weathering environment. For example, feldspars generally form the kaolinite group of minerals (kaolinite and halloysite), but may also form secondary mica (usually called sericite) and a number of other minerals such as gibbsite and sometimes montmorillonite. Gibbsite may form as a transitional product in kaolinite weathering of feldspars, but it may also be an end product under intense leaching conditions.

Biotite changes to hydrobiotite and vermiculite, with alteration initially commencing along structural planes of cleavage by oxidation and cation exchange. X-ray diffraction analysis of individual biotite grains in weathered granites in Australia by Gilkes & Suddhiprakaran (1979) showed that in the early and intermediate stages of weathering it is composed of interstratified micaceous minerals, vermiculite, kaolinite, gibbsite, goethite and locally hematite.

Mechanically, the minerals with good cleavage, such as feldspars and biotite, are particularly susceptible to fractures with attendant decrease in particle size and increase in surface area.

The progressive chemical and physical changes taking place in feldspars and other minerals in the weathering of acidic igneous rocks are illustrated in Figure 2.

## 3.4 Hydrothermal Alteration

Hydrothermal alteration is the decomposition of minerals due to the action of hot aqueous solutions, usually generated within a cooling intrusive body, that are released along joints and fracture zones during the final stage of igneous activity. Hydrothermal fluids may also originate from other sources including meteoric and connate waters.

Hydrothermal alteration has been an important process in the alteration of some granites and the rocks they have intruded. The effects produced by hydrothermal alteration and chemical weathering are similar and the end products are difficult to distinguish in most cases unless a special mineral assemblage is introduced by hydrothermal activity. For example, kaolinite is also produced by the hydrothermal alteration of feldspars via an intermediate micaceous mineral.

## 3.5 Weathering Profile

Continuous weathering results in the formation of a weathering profile grading from soil on the surface to unweathered rock at depth. Weathering profiles themselves can vary considerably from place to place, even in the same rock formation (Plates 1 and 2); as a function of variations in rock mineralogy and texture, mass structure, topography, rate of erosion, groundwater conditions, and climate. Granites, in particular, vary in the way they weather and events in their geological history may influence their later behaviour (Dearman et al, 1978). Cataclasis and shearing of the rock mass are also important (Newberry, 1970) which, coupled with hydrothermal alteration, may play a significant part in the development of weathering profiles (Irfan, 1977). It is the author's experience that these processes were also important in profile development and soil formation at many locations on igneous rocks of Hong Kong.

Although variable, a typical weathering profile in igneous rocks consists of four major zones. To avoid confusion, the term zone has been used here to describe the zonal arrangement of the weathering profile as distinct from the term <u>grade</u> used in the engineering classifications of the weathered rocks, although they are interrelated.

(a) Residual Soil Zone : A mantle of structureless soil the upper part of which may be transformed into laterite. This is underlain by;

(b) Saprolitic Soil Zone : A zone of soil-like material which retains features of the original rock structure and fabric and which may contain less weathered corestones of various sizes. This is underlain by;

(c) Transitional or Partially Weathered Rock Zone : A zone of partially weathered rock consisting mostly of rock separated by friable soil-like material along discontinuities <u>or</u> a continuous network of rock separated by seams of soil of varying thickness. This is underlain by;

(d) Solid Rock Zone : A zone consisting wholly of unweathered rock which may be stained along discontinuities or throughout but in which the strength of the intact rock is similar to that of fresh rock.

In subtropical regions with distinct wet and dry seasons, such as in Hong Kong, the soil zones are generally thinner than those found in tropical areas, and the fresher rock zones are more often encountered in excavations, particularly in mountainous terrain.

The residual soil zone in Hong Kong is not very well developed. This may be underlain by a 'transitional' soil zone similar to the saprolitic layer which retains part or most of the original rock fabric but no structure (Irfan, 1988). This zone may be up to 6 m thick and occur even on sloping ground as was observed on a slope adjoining Ching Cheung Road, East Kowloon (Irfan & Cipullo. 1989).

Poor residual soil development may indicate that the profiles in Hong Kong are immature. However, rapid sheet erosion, gullying and other mass wasting processes in a wet climate, might have removed the residual soil cover or at least arrested its formation. Mass wasting processes were particularly active in the Territory in Pleistocene times (Lai & Taylor, 1986) resulting in thick accumulations of colluvial deposits on the lower slopes of the mountains (Irfan & Tang, 1992). The present prevailing subtropical conditions might also not have allowed development of thick residual soils. A discussion on the age of weathering in Hong Kong is given in Bennett (1984).

A common feature of the weathering profile in igneous rocks in Hong Kong is the development of corestones. In general, corestone development is very common in the coarser grained and more widely-jointed granites (Plates 1 and 3), quartz-syenites and coarse ash and lapilli tuffs, whereas it is much less common in the finer grained or more closely jointed equivalents (Plate 2). The residual soil-saprolitic soil layer is thicker on granites and granodiorites than in the other rocks, reaching up to 60 m or more, but usually in the range of 20 to 40 m and deeper in fault/shear zones or areas affected by dyke intrusion or hydrothermal alteration (Plate 4).

Structural discontinuities within the rock mass are of the important controls of both chemical weathering and hydrothermal alteration processes. In many cases, the later weathering effects are superimposed on the hydrothermal effects, usually separated by a time period of many millions of years.

The distribution of the two processes is important in civil engineering projects such as the prediction of site conditions and depth to rockhead. The criterion that weathering affects the surface and decreases downwards and hydrothermal alteration may extend to greater depth with no reduction in effects cannot be used for a reliable distinction between the two processes, particularly in small exposures. Detailed field mapping supplemented by laboratory studies, for example by determining the crystallinity indices, may be necessary to differentiate the end products of the two processes. Hydrothermal effects may be confined to certain discontinuity directions (e.g. cooling joints) formed prior to the alteration, and are usually associated with white clayey kaolin veins, quartz-kaolin veins or other mineral veins in Hong Kong (Irfan & Woods, 1988).

In areas of intense hydrothermal alteration, the rock fabric and texture may be completely destroyed, at times making the identification of original rock type difficult. Away from these zones, the effects of hydrothermal alteration decrease.

In rocks affected by both hydrothermal alteration and chemical weathering, the profile development is rather complex due to structural control by discontinuities, shear zones and the pre-altered state of the rock (Plate 2). Corestone development typical of the coarse-grained granites and the coarse tuffs may not occur in hydrothermally altered rock. Hydrothermal alteration not only controls weathering profile formation in rocks, but may also locally result in the formation of soil-like materials. Invariably, the effects of hydrothermal alteration are usually modified by subsequent weathering.

## 4. ENGINEERING CLASSIFICATION OF WEATHERED IGNEOUS ROCKS

### 4.1 Classification of Weathered Rock Profile

A number of geological and engineering geological schemes have been used to describe and classify the weathered rocks for various engineering purposes (Table 3). Many of these schemes have been based on the characteristics of the weathering profile observed in tropically weathered granitic rocks (e.g. Moye, 1955; Ruxton & Berry, 1957; Little 1967; GCO, 1984). A review and critique of various descriptive schemes, particularly those applicable to igneous rocks, can be found in Dearman et al (1978), Gamon & Finn (1984), Dearman (1984) and Martin & Hencher (1984).

In tropical regions the emphasis has been towards the classification of the uppermost zones of the weathering profile, i.e. the saprolite and the residual soil, (Gidigasu, 1975; Gordon, 1984; Wesley, 1988) as it is these materials that are commonly encountered in engineering works. A recent publication by the Geological Society Engineering Group Working Party (Geological Society of London, 1990) reviews various classification systems for these soils. This recommended a new pedologically and mineralogically-oriented classification scheme (Table 4).

In subtropical regions with distinct wet and dry seasons, such as Hong Kong, or countries which once had subtropical climates (e.g. Europe), attention has more often been given to the description of the full weathering profile. A six-fold mass weathering grade classification, first proposed by Little (1969), and later refined by Dearman (1976), to characterize various components of the weathering profile has found favour with various international engineering bodies (e.g ISRM, 1978; IAEG, 1981; BSI, 1981). The applicability of this six-fold engineering classification scheme (Table 3) to various rock types is clearly illustrated in Chapter 2 of the report on Tropical Residual Soils by the Geological Society of London (1990). This scheme is also generally applicable to local igneous, volcanic, sedimentary and metamorphic rocks in Hong Kong (e.g. Irfan & Powell, 1985 for granodiorite; Choy et al, 1987 for granites; Greenway et al, 1987 for metamorphic rocks and GCO, 1990 for marble and metasedimentary rocks). It should be emphasized that this mass classification scheme is not a zonal scheme representing an idealised weathering profile. Mass grades can occur anywhere in the rock mass rather than in an idealised upward sequence from least to most weathered.

A six-fold rock mass weathering classification scheme based on GCO (1984), which is a modified form of the four-zone geological scheme set up by Ruxton & Berry (1957), has been recommended in Geoguide 3 : Guide to Rock and Soil Descriptions (GCO, 1988). Although this scheme is also based on the same criteria of differing proportions of 'rock' and 'soil' and the presence or absence of mass structure and material fabric, it differs from BSI (1981) in the terminology used and the definition of some zone boundaries (Table 3). The terms such as PW for partially weathered, UW for unweathered rock are used in this scheme to dispel the confusion which has existed in Hong Kong since the late 1970s over the misuse of terms generally adopted for the rock material (e.g. moderately decomposed) to describe the mass. The terms describing the weathering states of rock material, called 'the material grades', have been retained in the new GCO (1988) scheme. The terms used by GCO (1988) for describing the progressive change in rock material with weathering are also adopted in this document but with modifications as explained in Section 9 to take into account the effects of processes other than chemical weathering.

Both descriptive classification schemes have limitations, particularly for the characterization of the soil zones of the weathering profile. As demonstrated by Wesley (1988), Geological Society of London (1990) and recently by Wesley & Irfan (1994, see Table 5) there is a need to subdivide the soil zones into soil types of similar engineering behaviour based on mineralogical, micro- and macro-structural properties as a supplement to the broad groupings defined as parts of the weathering profile. This is discussed in the next section. Applicability of these tropical residual soil classification schemes to the soils formed from granitic rocks in Hong Kong is discussed in Section 10.4 in the light of the mineralogical and structural evidence compiled on these rocks.

For hydrothermally altered rocks, the terms used for the description of material or mass grades can be used (e.g. completely decomposed) as decomposition is a general term used for chemical changes including solution of mineral constituents. If the effects are recognised, a subscript A can be used to indicate that it is hydrothermally altered. Similarly for the rock masses, the term 'altered' can be used to describe rock masses which have been affected by hydrothermal alteration (e.g. slightly altered rock mass).

## 4.2 Classification of Residual and Saprolitic Soils

Geotechnical engineers elsewhere in the world have for many years made use of pedological terms to designate various soil groups. Terms such as lateritic soil, andosol, vertisol and black cotton soil found their their way into the soil mechanics literature. The mineralogically oriented scheme proposed by the Geological Society of London (1990) also uses pedological terms to classify the major tropical soil groups. However, it is complex and uses many terms unfamiliar to geotechnical engineers. The greatest weakness of the system is that it does not account for the structural characteristics of saprolitic and residual soils. After all, it is the structural properties of these soils that distinguish them from the sedimentary soils and contribute very strongly to their differing behaviour in the field and the laboratory.

It is precisely the dual influence of composition and structure which forms the basis of the universal classification system recommended by Wesley (1988). This system was modified by Wesley & Irfan (1994) and presented to the International Society for Soil Mechanics and Foundation Engineering (ISSMFE) Subcommittee on Tropical and Residual Soils (Table 5). In this system, the three main residual and saprolitic soil groups (A to C) are divisions based on composition alone without reference to their undisturbed state. The subgroups (a to c) are divisions based on the influence of the structure.

> Composition refers to both physical composition (e.g. % of unweathered rock, particle size, shape, etc.) and mineralogical composition, and
>
> Structure refers to both macro-structure (e.g. relict joints, layering, presence of unweathered or partially weathered rock) and micro-structure (e.g. microfabric, interparticle bonding, both primary and secondary, aggregation of particles, pores, etc.)

This system is useful in providing an overall global picture of the family of residual and saprolitic soils. It also has similar features with the traditional methods of classification and description for sedimentary soils which consist of two parts :-

(a) the classification of the material itself without any reference to the undisturbed state (i.e. soil material), and

(b) the description of the soil in its undisturbed state, e.g. stiffness, relative density, bedding planes (i.e. soil mass).

Wesley & Irfan's system is based on a grouping framework to enable the geotechnical engineers to place any particular soil formed from insitu weathering of rocks into a specific category on the basis of common engineering properties. The system is not intended as a replacement for any of the particular methods of classification at present in use whether it be a standard method such as the Unified Soil Classification System, or a method proposed specifically for weathered rocks (e.g. BSI, 1981), but rather as a supplement to them.

## 5. METHODS OF CHARACTERIZATION OF WEATHERED AND ALTERED ROCKS

### 5.1 General

The mineralogical and fabric changes occurring in rocks with weathering and alteration can be studied by means of a number of chemical and petrographical techniques available. These changes can also be indirectly assessed by means of simple field and laboratory mechanical index tests. It is important that the mineralogical and fabric properties are determined accurately since it is these properties that will control the engineering properties of weathered rocks and their behaviour in engineering works (Vaughan, 1985, 1988; Massey et al, 1989; Geological Society of London, 1990). As for the assessment of degree of weathering in the rock material and, indirectly, in the rock mass, the properties determined need to be characterized (quantified) as far as possible in order to establish relationships with the engineering and other properties. Quantification of weathering effects as index values also leads to consistent and objective material descriptions, particularly for the non-specialist user.

### 5.2 Chemical and Petrographical Methods

There have been several attempts to quantify the degree of weathering and the weathered rock fabrics by using chemical, petrographical, X-ray diffraction and electron microscope methods, or by simple field and laboratory mechanical and physical index tests (Table 6). Although in most cases, the quantitative and semi-quantitative weathering indices have been derived for the purpose of quantifying the change in purely geological properties, some quantitative weathering indices have been used to relate and to indirectly determine the engineering properties of weathered rocks (e.g. Dearman & Irfan, 1978). Many of these weathering indices have been specifically developed for characterizing the coarse-grained igneous rocks, particularly the granites. Some of the quantitative weathering indices have also been applied to the fine-grained igneous rocks (Weinert, 1964; Dearman et al, 1987).

The chemical indices, such as the weathering potential index (Reiche, 1943), ignition loss (Suoeka et al, 1985), and the specific gravity of feldspars (Matsuo & Nishida, 1968), can be a relatively accurate measure of degree of chemical alteration in the rock material. However, the engineering properties of weathered rocks are also dependent on the rock fabric and bonding, even in the soil grades. For example, granite and rhyolite in Hong Kong have similar chemical and modal compositions, but the physical and engineering properties are significantly different at similar degrees of weathering (Lumb, 1965).

Standard petrographic modal analysis and other techniques have been used for the whole spectrum of weathered igneous rocks to quantitatively evaluate the successive mineralogical and textural changes brought about by weathering. These include microcrack determinations (Onodera et al, 1974; Irfan & Dearman, 1978a), modal analysis of the percentage of decomposed minerals (Weinert, 1964; Mello Mendes et al, 1966; Irfan & Dearman, 1978a). Quantitative petrographic indices derived from these methods have been directly correlated with a variety of physical and mechanical properties of weathered granites (Onodera et al, 1974; Dearman & Irfan, 1978).

## 5.3 Physical and Mechanical Methods

Many different mechanical tests have been used primarily for rapidly and economically estimating the material design parameters (strength and deformability) and for characterizing the degree of weathering (Table 6). Good correlations have been reported between the test indices and the engineering properties of weathered granites (Hamrol, 1961; Onodera et al, 1974; Irfan & Dearman, 1978b). The Schmidt hammer, hand penetrometer and slake tests have been used for classification purposes to broadly distinguish between the soil grades of weathering, for example, between the highly and completely decomposed granites (Hencher & Martin, 1982).

Sowers (1985) considered that the void ratios and the degree of saturation are probably the only reliable simple indices that can be used to assess the degree of weathering of the soil grades. Specific gravity of feldspars in combination with void ratios have been used by Nishida & Anyama (1985) to classify weathered soil into four types for slope stability purposes. There is scope for developing special laboratory classification tests (see, for example, Vaughan et al, 1988), but these can only be useful when combined with fabric observations.

## 5.4 Microfabric Characterization

The objective of any study should be to classify and quantify the various fabric aspects in order that these can be correlated with engineering properties. Although the fabric of any geological material exerts a fundamental influence on its engineering properties, the relationship is difficult to interpret because of the level of complexity of fabrics in the weathered rocks and the intuitive nature of their interpretations (Collins & McGown, 1974; Baynes & Dearman, 1978b). Fabric in a weathered rock reflects the duration and intensity of weathering, and it is common to find very variable fabrics within the same specimen, indicating the marked variability of weathering microenvironments (Baynes & Dearman, 1978a; Massey et al, 1989). In the case of acid igneous rocks, the fabric is related to the degree to which feldspars have been weathered, to the proportion of clay produced during the decomposition process, and also to the extent to which particles have been eluviated from the system. The finer fabric features (mineral microfabrics) are beyond the resolving power of the ordinary microscope. These can only be studied by electron microscopy.

Various fabric configurations have been proposed to explain the observed engineering properties. For example, Baynes & Dearman (1978b) superimposed two simple fabric models on a void ratio-degree of decomposition index ($X_d$) plot. Collins (1985a) proposed a microfabric characterization scheme (Figure 3) for use in engineering studies, particularly for saprolitic and residual soils, to provide a rational and solid framework which can be extended and added to, as the need arises. These studies, supplemented by data obtained using other identification methods such as X-ray diffraction and electron microscopy, can help in understanding the engineering behaviour of weathered rocks.

The $X_d$ index which was used by Baynes & Dearman (1978b) and Collins (1985b) as a basis for microfabric characterization was found to be affected by the degree and type of pretreatment and iron-oxide cementation (Irfan, 1988). The micropetrographic index, $I_p$, described by Irfan & Dearman (1978a) may be used to characterize decomposed rocks whether the decomposition results from hydrothermal or weathering processes, in terms of its physical and chemical state. The other advantage of this technique is that it gives insight into the changing mineralogical and microcrack regimes involved in progressive weathering.

## 6. PREVIOUS WORK ON HONG KONG WEATHERED ROCKS

Little published systematic data exist on the mineralogy and particularly the fabrics of weathered igneous rocks in Hong Kong and these are usually confined to a few samples collected from a limited number of rock types (e.g. Brock, 1943; Parham, 1969; Lumb, 1962; Knill & Best, 1970; Lumb & Lee, 1975).

The most detailed study carried out on the mineralogical properties of weathered rocks can be found in an unpublished Ph.D. thesis by Kwong (1985). By means of petrological and electron microscopy and XRD techniques, Kwong studied the sequential mineralogical and fabric changes in four granites and one volcanic rock in conjunction with his research into the effects of geological and environmental factors on the engineering properties of weathered igneous rocks.

Recently, Irfan (1988) and Massey et al (1989) published some of the preliminary results of fabric work undertaken primarily on the saprolitic soils formed from two granitic rocks. The authors also attempted to relate the shear behaviour of the granitic saprolitic soil to its observed fabric properties.

Although data available on Hong Kong weathered rocks is limited, extensive data exist in the literature from systematic fabric and mineralogical studies carried out in the countries having similar igneous rock formations, in particular the granites (e.g. Irfan & Dearman, 1978a; Brenner et al, 1978; Baynes & Dearman, 1978a, b; Gilkes & Suddhiprakaran, 1979; Raj, 1985).

## 7. METHODS USED IN THE PRESENT STUDIES

A number of chemical, petrographical and physical test methods were employed in determining and characterizing the petrographical and index properties of weathered granite in Hong Kong through a number of in-house geotechnical projects and research work together with external research consultancies and other scientific collaborations. Some of the laboratory analyses reported in this document were carried out by Dr S. R. Hencher and Dr E. J. Ebuk at Leeds University under a GEO research consultancy, and by Dr O. A. Awoleye (under supervision of Dr P. Smart) at Glasgow University as part of his post-graduate research, as well as by Dr L. R. Dobereiner at LCPC in Paris on samples provided by the GEO.

The chemical and petrographical methods employed in each study varied from one to the other, based on the purpose of the study.

In-house mineralogical and fabric analyses were undertaken by the author. Chemical and X-ray diffraction analyses were carried out at a number of overseas commercial laboratories. In summary, one or more of the following chemical and petrographical methods were used in each study:

(a) Standard engineering geological description of hand specimens.

(b) Chemical analyses, in order to determine chemical and normative mineralogical composition by X-ray fluorescence spectrometry (XRF), inductively coupled plasma atomic emission spectrometry (ICPAES) or atomic absorption spectroscopy (AAS). Loss on ignition (LOI) and moisture determinations were also made.

(c) X-ray diffraction (XRD) analysis, on bulk samples and the clay fraction by employing various treatment techniques in order to determine the bulk and clay mineralogy.

(d) Optical microscopy, on thin sections in order to determine and quantify the mineralogical composition and fabric properties (e.g. grain boundary relationships, voids, weathering state of the mineral constituents and their arrangement). This work was carried out in-house.

(e) Scanning electron microscopy (SEM) and transmission electron microscopy (TEM), to study the fabric elements in more detail. Detailed studies were carried out only on the soil grades of Shouson Hill granite by Glasgow University (Awoleye, 1991). Limited SEM studies on thin sections of some weathered granite samples were carried out by Dr Dobereiner at LCPC in France.

(f) Electron diffraction (ED), infrared spectroscopy (IS) and differential scanning calorimetry (DSC) by Awoleye (1991) on the soil grades of Shouson Hill granite.

Details of these techniques can be found in standard textbooks and publications, (e.g. Grim, 1962, 1968; Gillott, 1968; Brindley & Brown, 1980; Jeffery & Hutchison, 1981; Smart & Tovey, 1982; Wilson, 1987).

# 8. DESCRIPTION OF TYPE SAMPLING LOCATIONS AND ROCK MASS PROPERTIES

## 8.1 General

Mineralogical and microfabric studies were carried out on two granites from the following localities :

(a) a megacrystic medium- to coarse-grained granite from King's Park, Kowloon,

(b) a medium-grained granite from Shouson Hill, Hong Kong Island.

## 8.2 Granite from King's Park

The sampling site at King's Park is situated on the western upper flank of a small hill rising out of the relatively flat Kowloon Peninsula (Figure 1). The granite occurring at the site comprises feldspar megacrysts, up to 20 mm in size, set in a medium-grained groundmass of quartz, feldspars and abundant biotite. The biotite content (over 10%) is generally higher than other granite types in the Territory. Variations both in grain size and the biotite content occur in the site and, in places, the rock assumes a coarse-grained texture.

The saprolite at the site is over 30 m thick, with occasional corestones, up to 4 m in diameter. Residual soil might have developed over the hill, but because of levelling of the top and excavation on the hillside, this layer has now been largely removed. The saprolitic soil, particularly in the vicinity of the sampling location is unusually deep reddish brown in colour. At places, cementation by iron-oxides is strong enough to produce a weak rock which still retains most of the original rock fabric. Iron-oxide veins present in the fresher rock outcrops, kaolin veins and the complete alteration of feldspars to clay minerals are all attributed to the effects of hydrothermal alteration. In others areas, the soil assumes the usual yellowish brown colour with feldspars showing less decomposition, typical of many of the granitic saprolites in the Territory.

The samples analysed from this site included the remainder of block samples of saprolite used for GCO's shear strength research in the late 1970s and early 1980s (Massey, 1979) and specimens of 'fresh' granite taken from corestones. Descriptions of the samples are given in Appendix A.

## 8.3 Granite from Shouson Hill

The sampling site at Shouson Hill, Hong Kong Island (Figure 1), occupies part of a relatively flat hilltop together with the side cut slopes (10 to 15 m high) which were re-formed in the mid-1980s. The granite is of a commonly occurring medium-grained type found underlying the northern part of Hong Kong Island and Kowloon peninsula. In the fresh state, it is light pinkish grey and consists of quartz, alkali and plagioclase feldspars and a small amount of biotite.

The granite on the site is weathered to a saprolitic soil to a depth of over 30 m (Figure

4, Plate 5). A 1 to 2 m thick reddish brown residual soil is developed over most of the hilltop area. The majority of the saprolite is composed of material which would be broadly described as completely decomposed granite, to a depth of about 10 to 15 m. It becomes progressively denser and less decomposed (particularly the plagioclases) with depth and below about 15 m it would be mostly described as highly decomposed granite (Figure 5). However, considerable lateral and vertical variations resulting from chemical decomposition, physical disintegration and localised hydrothermal alteration occur throughout the site (Figure 4). Hydrothermal alteration has been particularly intense adjacent to quartz and kaolin veins (Plate 6), with all the feldspars completely decomposed to white clayey kaolin pseudomorphs.

Within this general matrix of chemically decomposed granite, there are corestones and other areas where the feldspars show little decomposition but the rock is weathered to the condition of friable soil as a result of mechanical disintegration. This material would also be normally described as 'completely decomposed granite' using the terminology given in GCO (1988). Nevertheless, it would have very different engineering properties when compared with the completely decomposed granite showing higher feldspar decomposition. Similarly, the hydrothermally altered granite would also have significantly different engineering properties with the shear strength, for example, reduced to as much as half of the normally weathered type (Irfan, 1988; Massey et al, 1989).

The transition from saprolite to residual soil is gradual. Very few relict structures (e.g. joints) are preserved in the transition zone which still retains most of its decomposed granitic fabric. In one of the trial pits used for sampling, a 'residual soil' seam was present at a depth of 5 m. This seam might have formed as a result of intense hydrothermal alteration or biological weathering in the vicinity of tree roots or by a combination of the two processes.

Several block and hand samples were collected from different weathered materials (Figure 5) in order to characterize the mineralogical and fabric changes occurring in granites, in general, and for various strength testing programmes (e.g. Cheung & Greenway, 1987). Brief descriptions of the samples are given in Appendix A.

## 9. MATERIAL WEATHERING GRADES IN GRANITE

### 9.1 Classification and General Characteristics

The material weathering grades (classes) used in this document are broadly based on the definitions given in GCO (1988) with subdivision of some of the grades as explained below. The term 'decomposed' is retained in place of the more appropriate term 'weathered' in order to avoid confusion between the definitions applied to the weathering state of the rock mass (based on BSI, 1981) and the rock material (based on GCO, 1988).

Although the dominant process is chemical weathering (decomposition) in Hong Kong, the rocks may locally show the effects of hydrothermal alteration and also more recent physical weathering as explained in previous sections. It should be emphasized that the weathering effects are progressive and variations in material grades can occur laterally as well as vertically in any rock mass.

### 9.2 Fresh Granite

In the hand specimen, all the mineral consituents are hard and sound. The overall rock colour varies from light grey to pinkish grey in Hong Kong granites. Fresh granites are generally very strong rocks with the fine-grained varieties being extremely strong (Irfan, 1994a).

### 9.3 Slightly Decomposed Granite

By definition (GCO, 1988), this grade of rock can show up to 100% discoloration, usually by dark to light yellowish brown staining. Plates 7 and 8 show the hand specimens of granite weathered to different degrees. The slightly decomposed rock grade can be divided into three subgrades depending upon the amount of discoloration which is indicative of progressive weathering taking place in the rock :

(i) Slightly Discoloured Granite (less than 10% discoloration);

(ii) Moderately Discoloured Granite, (10% to 50% discoloration) and;

(iii) Highly Discoloured Granite (over 50% discoloration).

In the Moderately Discoloured Granite, the core may also show a slight discoloration to pale yellowish grey, usually surrounded by a narrow dark brown band and a wider light brown to yellowish brown band. In some cases, a series of microcracks parallel to major joint surfaces are present in the stained zone. These microcracks are considered to be the result of stress release aided by slight chemical decomposition of feldspars and biotite in the vicinity of joints. At more advanced stages of weathering, these microcracks develop in a radial arrangement surrounding the less weathered corestones. In the stained rims, some feldspars are gritty indicating slight chemical alteration (see Table 7 for the definition of grittiness terms).

### 9.4 Moderately Decomposed Granite

The rock material is completely discoloured yellowish brown (Plate 7). Plagioclase feldspars are gritty, alkali feldspars are hard but they may also be gritty due to microfracturing in the more weathered specimens. The intact rock strength is appreciably reduced in the more weathered specimens in this grade, in comparison to the fresh and slightly decomposed granite.

### 9.5 Highly Decomposed Granite

The rock material is highly microfractured by through-going microcracks. A highly decomposed granite can be a weak rock (with a uniaxial compressive strength of up to 10 - 15 mPa) in the least weathered state in accordance with the definition given in GCO (1988), i.e. "can be broken by hand and Schmidt hammer value up to 25". Most plagioclases are powdery to gritty and alkali feldspars are hard to slightly gritty in the weak rock range. In more intensely weathered, very weak rock specimens in this grade, all plagioclases are powdery to soft.

## 9.6 Completely Decomposed Granite

In general, the rock material is completely discoloured yellowish brown to yellowish grey, but may also be mottled (Plate 8). It can be disintegrated into individual soil grains with slight to moderate finger pressure. The granitic fabric is present with soft to powdery plagioclases still retaining their grain outlines. Alkali feldspars are largely undecomposed but appear gritty due to intense microfracturing. In specimens affected by hydrothermal alteration, all feldspars may be soft to powdery.

Irfan (1988) recognised four subclasses of soil material within the 'completely decomposed granite' grade as defined in GCO (1988), based on the degree of decomposition of mineral constituents, the type of weathering (disintegration or decomposition) and the degree and type of alteration. These are :

(a) (normally) Decomposed Granitic Soil

(b) Disintegrated Granitic Soil (with little decomposition)

(c) Altered Granitic Soil (affected by hydrothermal alteration)

(d) Transition Soil (with partial fabric loss). This type is treated separately in the next section.

Transitions commonly occur amongst these types and any decomposed sample may show varying effects of alteration and disintegration. A further subdivision can also be made based on (relative) strength, which is in fact a function of its degree of weathering and alteration :

Loose, Dense or Very Dense (Decomposed, Disintegrated or Altered) Granitic Soil

This subdivision can be based on laboratory or insitu density measurements, field probing (GCO probe or standard penetration) or any other relative strength or consistency determinations (see Section 11). In general, the soil density or strength increases broadly with depth but rapid variations can occur laterally due to variations in soil mineralogy and fabric. In some cases, variations in fabric and other properties (e.g. colour) are too subtle for positive identification of different types in the field, but in most cases, a laboratory study may be needed, particularly for the specimens showing the effects of more than one process.

## 9.7 Transition Soil

Transition soil specimens are discoloured light yellowish grey to reddish brown, but they may also be mottled. The material shows partial loss of the decomposed granite fabric throughout. In the transition soil zone, en masse, the rock structure is also largely destroyed resulting in a gradual disappearance of relict discontinuities and other mass features upward in the weathering profile. Biotite is mostly changed to soft, colourless to silvery grey flakes and quartz shows a significant loss of lustre.

### 9.8 Residual Soil

The granitic fabric is completely destroyed. The soil material is discoloured yellowish brown to reddish brown, but it can also be yellowish grey when leached of its iron minerals. Decomposed feldspars are no longer visible. It comprises quartz grains in a structureless clayey silt matrix which may be weakly cemented by iron minerals.

Residual soil formation in Hong Kong is not at an advanced stage and more mature soils rich in iron and aluminium (e.g. ferricretes and ferrallitic soils, see Geological Society of London, 1990), which are typically found in hot humid tropical countries are not present.

## 10. MINERALOGY AND FABRIC PROPERTIES

### 10.1 Mineralogical Properties

The results of chemical analyses of granite specimens weathered to different degrees are given in Tables 9 to 11, arranged in order of grade. The results of semi-quantitative and quantitative mineralogical and fabric analyses from the microscopical and XRD studies are presented in Tables 12 to 15. Selected typical XRD patterns are shown in Figures 6 to 8. Variation in major oxides contents with weathering is represented by schematic diagrams in Figures 9 and 10.

Variation in mineralogical and pore composition of Hong Kong granites with weathering, using Shouson Hill site as a typical example, is represented by Figure 11. A summary of possible paths of mineral transformations in Hong Kong granites is given in Figure 12. Detailed descriptions of mineralogical and fabric properties of each grade of granite derived from the various chemical and petrographical studies are given in Appendix B.

#### 10.1.1 Fresh Granite

The major constituents of Hong Kong granites are plagioclase, alkali feldspar and quartz with minor amounts of micas (usually biotite). A small amount of hornblende may be present in some varieties. Small amounts of accessory minerals such as sphene, apatite, zircon and pyrite are also present. The quartz content is usually between 30% and 40% and the mica content is less than 5%. However, the mineralogical composition can vary throughout each granite type or pluton. Hong Kong granites also show significant variations in their texture, varying from inequigranular or equigranular fine-grained to megacrystic coarse-grained. Very coarse-grained (over 20 mm in grain size) pegmatitic granitic veins/areas may also occur locally. These variations in texture can also be present at individual sites. Detailed petrographic descriptions of various granite types occurring throughout the Territory can be found in the Geological Survey Memoirs, some of which are listed in the references.

The overall quartz content of the granite samples from King's Park and Shouson Hill are very similar (about 35%), although it varied between 28% and 41% in various thin sections for the latter (Table 8). The granite from Shouson Hill has a broadly equigranular medium-grained texture with an average grain size of 1 to 4 mm. Occasional large feldspars up to 10 mm in size are also present. In contrast, the granite from King's Park has a variable medium- to coarse-grained megacrystic texture with feldspar crystals up to 20 mm.

Even in the freshest granite specimens studied (Plates 9 and 10), plagioclases showed a small amount of micaceous mineral growth (sericite). Most of this alteration, which may also be present as partial replacement of alkali feldspars, is probably the result of late stage magmatic processes including hydrothermal alteration. Similarly, a small amount of chloritization of biotite in the fresh granite can be attributed to such alteration processes.

#### 10.1.2 Slightly Decomposed Granite

Alteration of plagioclases increases with increasing discoloration in the slightly decomposed granite grade (Plate 11). The SEM images of the discoloured portions of the Shouson Hill specimens revealed the development of solution features in the feldspars in this grade (Plate 12). The same phenomenon was also observed by Kwong (1985) on a number of Hong Kong granites. These findings confirm the work of Berner & Holdren (1977) and Baynes & Dearman (1978b) that initial stages of weathering are marked by solution along grain boundaries and within the feldspars. Biotite also starts to alter to mainly micaceous products in the early stages of weathering, particularly along the cleavage planes and grain boundaries.

#### 10.1.3 Moderately Decomposed Granite

Kaolin minerals start to form in small amounts in the plagioclases in the moderately decomposed grade (Plates 13 and 14). Numerous isotropic 'growths' or 'speckles' were observed in the plagioclase grains under the microscope. These might represent an intermediate amorphous alumino-silicate mineral on the way to kaolinite or halloysite (termed allophane by Parham, 1969 and Lumb & Lee, 1975). Electron microscopy by Awoleye (1991) identified some of these minerals as clusters of halloysite tubes growing directly out of unaltered portions of individual grains in the more weathered specimens (Plate 18). It is still possible for the amorphous intermediate minerals to form first on feldspar surfaces prior to transformation into halloysite. Some or many of these growths might also be the locations of dissolution pits and pores.

Alkali feldspars are only slightly altered but they develop some internal microfracturing. Quartz is mostly unaltered but it shows the development of intragranular and transgranular microcracks (Plate 14).

#### 10.1.4 Highly Decomposed Granite

Near-complete alteration of plagioclases occurs in the highly decomposed granite grade, accompanied by significant solution of alkali feldspars (Plates 15 and 16). The quantitative petrographic analysis shows that more than 50% of the feldspars are altered in the more intensely weathered specimens in this grade (Table 12). Plagioclases are mostly decomposed to halloysite, with some micaceous products which are possibly retained from the earlier stages of weathering and alteration. The SEM backscatter images of the decomposed plagioclases show the growth of crystalline kaolin minerals (halloysite?) in a dominantly poorly crystalline to amorphous clay mineral matrix (Plate 16). The XRD traces indicate trace to nil amounts of plagioclase (Figure 7, Tables 14 and 15).

An important aspect of alkali feldspar weathering in this grade is the formation of dissolution features as pits, trenches and channels visible under the microscope (Plate 16). These features are particularly well-developed in the albitic (plagioclase) lamellae of the perthitic feldspars. It is not known whether these features are formed as a result of direct removal of cations by solution or if they are the locations of secondary mineral growths which have subsequently been removed by solution. Eggleton (1986) observed that although K ions are highly mobile, the alkali feldspar is relatively resistant to decomposition because the framework structure of the tetrahedra restricts their escape and those chains must be first broken to free cations. This probably happens in the highly decomposed granite where extensive fracturing of the rock fabric and individual feldspars occurs. Chemical analysis shows a noticeable reduction in $K_2O$ content of the more intensely weathered sample within this grade, confirming that some K ions are removed from the system (Figures 9 and 10). Biotite continues to decompose to a mixture of kaolin minerals, muscovite, chlorite and iron-oxides. Slight expansion (exfoliation) of altered biotite, which is now visible under the microscope, may also occur in some grains.

Kaolin and micaceous mineral content varies from about 10% by weight of the total rock in the least weathered specimens to about 20-30% in the most weathered specimens in the highly decomposed granite (e.g. see Table 12).

### 10.1.5 Completely Decomposed Granite

In the completely decomposed granite (Plates 17 to 23), a wide range of variations occur in terms of soil mineralogy and fabric depending on the type and degree of alteration processes and the local environmental factors including topography and drainage conditions. The recent changes brought about by man's activity may also result in rapid modification of soil mineralogy and structure (Irfan, 1994b). In general, plagioclases are completely decomposed but some partially decomposed grains may still be present in the disintegrated type. This type of soil is usually formed by rather rapid present day weathering (disintegration) of highly decomposed corestones when they are exposed on or near the surface by recent slope cuttings.

Although halloysite is the predominant clay mineral (Table 15), a significant amount of kaolinite may also be present in the specimens affected by hydrothermal alteration (Figure 8). In well-drained sites, leaching of clay minerals may lead to development of a porous structure in the decomposed plagioclase grains. The kaolinite content increases progressively with increased weathering and may form up to 50% of the total clay mineral content (Tables 12 and 16), particularly in near surface transition and residual soil specimens. The majority of kaolinite is probably formed from halloysite tubes. Some kaolinite may also be produced directly by the decomposition of alkali feldspars. Small quantities of fine grained micaceous minerals (most probably 2Ml muscovite or illite) are present in all specimens, with the proportion decreasing upwards in the weathering profile (Figures 6 and 7).

Alkali feldspars develop very variable and porous to honeycombed microfabrics in this grade (Plate 23), particularly in reasonably well-drained sites such as Shouson Hill. Solution appears to be the dominant process resulting in the formation of numerous pores and channels particularly at the sites of sodic lamellae.

Many of the solution pits or channels have irregular sidewalls indicating that the compositional control (preferential solution of sodic areas) is more dominant than the structural control in the weathering of the perthitic alkali feldspars. The SEM observations showed severe etching, particularly in the near-surface specimens, forming highly honeycombed, fragile alkali feldspars. Coalescence of prismatic etch pits at advanced stages of dissolution may also form irregular-sided channels (Baynes & Dearman, 1978b). In contrast, alkali feldspars show some decomposition to clay minerals (mostly kaolinite) in granites affected by hydrothermal alteration; they may even be completely replaced by kaolinite if alteration is intense. The XRD analyses of altered specimens from King's Park revealed the presence of a significant amount of kaolinite occurring together with halloysite (Figure 8). It is possible that some kaolinite has been formed directly from the alteration of alkali feldspars.

Biotite is almost completely altered to a variety of secondary minerals in the completely decomposed grade, with many grains showing expansion along cleavage planes, particularly in the near surface and disintegrated soil specimens (Plate 21). Awoleye et al (1988) observed tubes of halloysite growing on biotite in the completely decomposed specimens from Shouson Hill. Eswaran & Bing (1978) also observed the growth of tubular halloysite from weathered biotite grains in saprolitic and lateritic soils developed over a granite in Malaysia. In the granitic saprolitic soils of Southwestern Australia, Gilkes & Suddhiprakaran (1979) reported the formation of various interstratified micaceous minerals, vermiculite, kaolinite, gibbsite, goethite and locally hematite from biotite. Vermiculite was not detected in any of the saprolitic and residual soil specimens from Shouson Hill and King's Park, but small amounts of chlorite were invariably present in each. Vermiculite was not identified in the studies carried out by Kwong (1985) and Parham (1969). However, vermiculite has been found to be present in small amounts in soils formed from biotite-rich acidic rocks affected by hydrothermal alteration (Irfan, 1994b) or in less well-drained sites (Suddhiprakaran & Gilkes, 1979). Also, based on the studies carried out elsewhere (Wilson, 1975), a small amount of smectite or more kaolinite than halloysite may form in less well-drained sites, particularly at valley bottoms.

The clay mineral content becomes significant in the completely decomposed grade, increasing to about 40% by weight, and even more if the rock has also been affected by hydrothermal processes (Table 16). The SEM and TEM studies on Shouson Hill specimens showed that the majority of the clay minerals are silt size (up to 9 Nm long) tubular halloysite clusters, with the proportion of clay size kaolinite plates increasing in the more weathered or altered near-surface soils. The remainder consists of sand to fine gravel size quartz and a small amount of porous to honeycombed alkali feldspars. The pore content is high, usually between 15 to 25% by volume, more in the disintegrated specimens (Tables 12 and 13). First noticeable solution of quartz occurs in this grade, as observed from chemical analyses of Shouson Hill specimens (Figure 9). However, constant volume analysis indicates a gradual but slight reduction in all stages of weathering (Figure 10), indicating a slow removal of silica from the system. The reduction in silica content may also be due to hydrothermal effects.

10.1.6 Transition Soil

Alkali feldspars gradually disappear from the soil in the transition soil grade (Plate 24). The final stage of alkali feldspar weathering is marked by their chemical alteration to clay minerals (mainly kaolinite) rather than solution. The majority of the fragile honeycombed feldspars have collapsed and disintegrated into very small fragments, which subsequently become more susceptible to chemical alteration. The clay mineral content attains about 50% by weight or over (Table 16), with kaolinite gradually becoming more dominant than halloysite (Figure 14). Quartz is still the dominant mineral composing up to half of the soil by weight. It shows minor effects of solution as indicated by pitting and etching marks on the grain surfaces and along the open microcracks.

10.1.7 Residual Soil

All the primary minerals, apart from quartz, are absent in the residual soil grade, except perhaps occasional alkali feldspar fragments (Plates 25 and 26). Quartz is broken up into smaller fragments and scattered throughout the clay mineral matrix. Kaolinite is the dominant clay mineral with some halloysite and a small amount of muscovite/illite. A small amount of gibbsite is also present.

10.1.8 Gibbsite and Iron-oxide Minerals

Formation of gibbsite is generally related to intense flushing of released constituents in well-drained sites (Loughnan, 1969) and this mineral is an important component of mature granitic soils. Gibbsite was not detected in the saprolitic soil specimens at Shouson Hill and King's Park or any of the granite sites studied by Kwong (1985). Lumb & Lee (1975) reported the presence of small amounts of gibbsite in the first few metres of the ground surface in 'decomposed granites' from Hong Kong. The minor occurrence of gibbsite in the reasonably well-drained granitic soil environment of Hong Kong indicates that these soils are probably immature. The saprolitic and residual soils in Hong Kong have been formed under a subtropical climate with the weathering processes being not as intensive as those found in the more tropical areas.

Gibbsite forms either from direct alteration of feldspars (Baynes & Dearman, 1978b; Gilkes & Suddhiprakaran, 1979) or from the secondary clay minerals (Loughnan, 1969). The occurrence of gibbsite only in the residual soil stage in Hong Kong, where all the feldspars have long disappeared, may be an indication that the gibbsite is formed from one of the clay minerals (probably kaolinite or halloysite), after they were formed from the primary minerals.

A small amount of iron-oxide minerals is present in the highly and completely decomposed granites (Table 11). These occur as coatings on the clay minerals and unaltered primary minerals and also as microcrack infillings. The main source of Fe in granites is the biotite. Iron released from the weathering of biotite is oxidized and precipitates largely as $Fe^{3+}$-oxides (e.g. hematite) and oxyhydroxides (e.g. goethite) (Lindsay, 1987). It is not easy to determine the type of iron mineral from XRD traces due to low concentrations of these minerals, their poorly crystalline nature and interference from kaolin reflections. Awoleye (1991), who used a combination of XRD, TEM, SEM, infrared spectroscopy, DSC and mineral concentration techniques, identified goethite as the main iron-mineral with minor quantities of poorly crystalline ferrihydrite (a ferric oxyhydroxide) in the Shouson Hill samples. The identification of goethite in soils from tropical and subtropical areas is well documented (e.g. see Schwertmann, 1987b for a review) and this mineral together with hematite, is common in saprolitic and residual soils from these areas. They are often responsible for the yellowish and reddish colours of most tropical soils. Although hematite was expected in the soil specimens, especially in the red mottles, the mineral was not identified by any of the techniques used by Awoleye (1991).

The absence of hematite from the completely decomposed granite and the co-existence of goethite with ferrihydrite led Awoleye (1991) to postulate that at least some of the goethite is formed via the ferrihydrite. Ferrihydrite is usually very unstable in tropical and subtropical soil conditions and transforms into more stable forms such as goethite. Slightly acidic pH range of soil water might have favoured formation of goethite over hematite from ferrihydrite at Shouson Hill. A detailed discussion on the formation of iron-oxide minerals in the weathered granite at Shouson Hill is given by Awoleye (1991).

Goethite is the predominant iron-oxide mineral (about 3% to 5% by weight of the soil) in near-surface residual soils developed over granite in Hong Kong. The crystallinity of goethite generally increases upwards in the weathering profile. It occurs throughout the soil as strong aggregations and may locally cement the clay and other particles together. Although hematite was absent at Shouson Hill, its presence in soils formed from weathering of magnetite-bearing granitic rocks, such as those found at King's Park, cannot be precluded. Gilkes & Suddhiprakaran (1979) reported the presence of hematite (altered from magnetite) in the 'mottled zone' (i.e. residual soil zone) formed over granites in Australia.

Iron and aluminium ions leached from near surface layers by infiltrating undersaturated rainwater as colloids or in solution can be concentrated at depth as iron and aluminium oxides and hydroxides. Iron-oxide formation which may result in partial cementation of clayey matrix is particularly active in the groundwater fluctuation zone (Selby, 1982). Such a zone was observed to be formed in a volcanic saprolite at a landslip site (Irfan, 1994b).

## 10.2 Fabric, Microfracturing and Pore Development

### 10.2.1 Fresh Granite

In the fresh granite, grain boundaries are tightly welded but microvoids can occur between grains (Baynes & Dearman, 1978b). Granites invariably contain short, tight or healed microcracks associated with stress relief during cooling (Sprunt & Brace, 1974). Microcracks may also be produced by tectonic stresses. In addition to these microcracks, other defects are also present in the minerals themselves, such as the cleavage planes in feldspars and micas. All of these act as pathways for the weathering agencies.

10.2.2 Slightly Decomposed Granite

In the initial stages of weathering, structurally-controlled solution features (i.e. prismatic etch-pits) are formed on the crystal surfaces of feldspars, primarily at the sites of dislocations (Berner & Holdren, 1977; Baynes & Dearman, 1978b). These are initially developed in the vicinity of joints or other fractures through which the weathering solutions penetrate the rock material. At the same time, Fe is released from biotite by oxidation and solution and stains the rock material along the existing microcracks and grain boundaries in the vicinity. This results in the discolouration or staining of the rock adjacent to joints and other fractures. Simple transgranular microcracks start to develop in the stained zone (Plate 11), generally parallel to the joint planes. Some of these may be formed by the extension of existing intragranular and intergranular cracks or voids. Some of the microfracturing may also be due to the expansion of biotite resulting from increased interlayer spacing of secondary minerals formed in biotite (Isherwood & Street, 1976; Irfan & Dearman, 1978a).

The majority of microfractures present in the slightly decomposed and higher weathering grades of granite probably arise from the destressing of quartz and feldspars during weathering. Increased porosity and opening grain boundaries of the feldspars caused by solution would lead to microfracturing by the release of residual stresses in quartz and other minerals (Baynes & Dearman, 1978c).

10.2.3 Moderately Decomposed Granite

A majority of the grain boundaries, including quartz to quartz contacts, are either stained by iron-oxides, which may indicate solution of grain surfaces, or microfractured in the moderately decomposed granite (Plate 13). A very significant reduction of intact strength occurs across this grade, from very strong to strong rock in the slightly decomposed state to very weak rock in the highly decomposed state. This is mainly due to increasing degree of microfracturing as the amount of mineral alteration is still small (Table 12). Solution pores, some connected, are present inside the feldspars (Plate 14), but these are generally less than a few microns in diameter.

10.2.4 Highly Decomposed Granite

With further weathering, the intensity of microfracturing increases, grain boundaries and microcracks start opening up and the voids are enlarged in the highly decomposed grade (Plate 15). Void formation by solution affects most alkali feldspars in this grade, and many join up to form irregular solution channels (i.e. etch-crevasses of Baynes & Dearman, 1978c). Numerous minute pores and smaller dissolution channels, only visible under an electron microscope, are also present amongst the halloysite grains or grain clusters growing out of highly decomposed plagioclases (Plate 18).

10.2.5 Completely Decomposed Granite

In the completely decomposed grade, a variety of fabrics and microfabrics is produced (Plates 17 to 23) depending on:

(a) the degree to which feldspars have been weathered,
(b) the type of clay minerals formed,
(c) the type of weathering or alteration process, and
(d) the extent to which particles have been eluviated from the system.

In general, there is an increase in the degree of microfracturing of the weathered rock fabric throughout by complex-branched, mostly open microcracks and macrocracks (over 1 mm in width). Most grain boundaries are open but some are still tightly interlocking and hence retain the original primary bonding.

Microfabrics developed in plagioclases can vary from dense, tightly packed halloysite tubes to porous tubular halloysite - platy cardhouse kaolinite mixtures to very porous networks of clay particles. Alkali feldspars generally develop extremely open, porous mineral structures (i.e. honeycombed), consisting of a framework of thin struts of feldspar left after coalescence of etch-pits, etch-trenches and etch-crevasses (Plate 23). In the 'disintegrated' types, a highly microfractured and porous fabric with little clay mineral content may form. In contrast, very dense clay fabrics (cf. kaolinite) with little microfracturing and sand (quartz) content may be present in the 'altered' types depending on the intensity of hydrothermal alteration.

The partially weathered feldspar structures may still be in continuous or partially continuous contact with the resistant quartz grains giving a true cohesion to the completely decomposed granite. In addition, clay and sesquioxide bridges may exist between the completely decomposed feldspar grains and the quartz grains (Collins, 1985a).

### 10.2.6 Transition and Residual Soil

In the transition and residual soil grades quartz grains are left as the only primary minerals in a denser clay mineral fabric. The microfractured granitic fabric is gradually lost upwards in the weathering profile, through a transition soil zone (Plate 24), due to localized collapse of highly porous 'metastable' soil structure and the soil transforms into a true residual soil with a much reduced void ratio near the ground surface (Yudhbir, 1982; Massey et al, 1989). Aggregation and weak cementation of clay minerals by iron-oxide minerals (mostly goethite but also hematite in some situations) may occur in the residual soil grade (Plate 26). In extreme cases of weathering or where abundant iron-oxide minerals are present in the original rock (e.g. King's Park granite), cementation of the clay particles and quartz grains may be strong enough to result in a lateritic soil typical of more tropical climates.

## 10.3 Characterization of Material Weathering Grades of Granite in terms of Mineralogical and Fabric Properties

A characterization of the material weathering grades of granites in Hong Kong is given in Table 17 in terms of their characteristic mineralogical and microfabric properties.

## 10.4 Classification of Granitic Residual and Saprolitic Soils

A classification of various soil types formed from insitu weathering of granitic rocks in Hong Kong is given in Table 18 in accordance with the classification scheme proposed by Wesley & Irfan (1994) (see also Table 5 and Section 4.3). Broad macro- and micro-structural properties and mineralogical composition of the soil types are also described in the table.

The soils of granitic origin generally fall in Group A, but also in Group C(c) if rich in sesquioxides. The formation of the latter group of soils is considered to be of minor occurrence in Hong Kong in comparison to those developed in tropical regions; these soils are loosely referred to as lateritic or laterite (Table 5).

It is possible that the halloysite content of saprolitic soils formed from quartz-poor rocks (e.g. syenites) may be significant enough to place these soils in Group C(b). The mineralogy of quartz-deficient igneous rocks have not been studied in any detail in Hong Kong. However, these soils should still be classified under Group A, as structural influences would still be dominant in controlling their behaviour. This is also considered to be the case for soils of granodiorite origin. A small amount of swelling minerals (e.g. montmorillonite and vermiculite) may form from decomposition of hornblende and biotite present in the rock, particularly in poorly drained areas.

Within Group A, based on their the mineralogical and structural properties documented in Section 10.2, the near-surface granitic soils (i.e. residual soil and transition soil zones, if present) would belong to Subgroup (c), upper portion of the Saprolitic Soil or the Completely Weathered Granite Zone to Subgroup (b), and the upper portion of the Highly Weathered Granite Zone with up to 30% weathered rock fragments to Subgroup (a). It would be more appropriate not to include the lower portion of the Highly Weathered Rock Zone in this soil mechanics classification since this zone would behave like a rock mass (see Irfan & Tang, 1992 and Table 18).

Almost all soil zones including the Highly Weathered Granite Zone in Hong Kong would be classified as 'Ferruginous (sensu stricto)' Soils, under the classification scheme proposed to the Geological Society of London (1990), except perhaps the uppermost Residual Soil Zone, which would be described as 'Ferrallitic (kaolinitic)'.

# 11. QUANTITATIVE WEATHERING INDICES

## 11.1 General

A brief review of the weathering indices proposed to assess the degree of weathering of rocks is given in Section 5. A number of the better known indices, particularly those applicable to the whole spectrum of weathering (Table 6), were selected and their numerical values were calculated for various weathered granite specimens in this study. This was done in order to determine if these indices could be used to quantity the mineralogical and fabric changes brought about by weathering and other alteration processes in the granitic rocks of Hong Kong. The indices thus determined can then be used to indirectly determine the engineering properties of weathered granitic and other igneous rocks (e.g. see Dearman & Irfan, 1978).

## 11.2 Chemical Indices

A list of the chemical indices selected for the characterization of the degree of weathering of igneous rocks is given in Table 19. The weathering indices calculated for the granite at Shouson Hill are presented in Tables 20 and 21.

A new index, the Mobiles Index, $I_{mob}$, has been introduced in this document to characterize the degree of weathering of feldspar-bearing igneous rocks. The formula for the calculation of $I_{mob}$ is given below :

$$\text{Mobiles Index } (I_{mob}) = \left[ \frac{Mob_f - Mob_w}{Mob_f} \right] \text{Mole}$$

where $Mob_f$ and $Mob_w$ are the total ($K_2O + Na_2O + CaO$) contents in the fresh and weathered rock, respectively.

This index gives a relative measure of the removal of the mobile cations from the rock with weathering and alteration. Hence, it serves as an index of the degree of decomposition of the feldspars, particularly in reasonably well-drained (leaching) conditions, such as those found in most hillsides and hilltops in Hong Kong. Figure 13 is a plot of $I_{mob}$ against the unaltered feldspar content (determined from modal analysis, Table 13) for the weathered granite from Shouson Hill. A linear relationship with a significant correlation is obtained.

An examination of the index values presented in Tables 20 and 21 reveals that all except the lixiviation index ($\beta$) and the alumina-to-calcium and sodium oxide ratio (ACN) are good indicators of the degree of weathering for granite. Figures 14 and 15 indicate linear relationships with good correlation coefficients for $I_{mob}$ versus WPI and SA ratio when hydrothermally altered specimens are excluded. The SA ratio has been found to be a good index of chemical weathering in most free draining, usually acid, weathering environments in humid climates, especially on acid and intermediate rocks that weather to kaolinite or illite group of minerals (Ruxton, 1968). This index is not suitable for weathering conditions which result in smectite or vermiculite minerals, especially for basic and ultrabasic rocks. Figure 16 gives a schematic illustration of variation in LOI content with weathering grade.

As pointed out previously, these chemical indices reflect only the broad mineralogical changes taking place in the rocks with weathering or other alteration processes. Weathering produces microfabric as well as mineralogical changes in the rock material and macrofabric changes in the mass.

## 11.3 Dry Density

Chemical weathering indices are only useful in engineering characterization of a rock if they can be related to some measurable physical or mechanical properties. With this in mind and in order to assess their relevance in weathering grade assessment, selected indices (WPI, $I_{mob}$, SA ratio and LOI) were plotted against their corresponding dry bulk densities. Only $d_d$ versus LOI and $I_{mob}$ plots are presented in Figures 17 and 18. The dry densities of the transitional and residual soil specimens were not included in the plots. Dry density starts to increase in these materials due to the collapse of porous soil fabric, deposition of heavier sesquioxide minerals and the removal of lighter clay particles by leaching.

Dry density values plotted in the figures are those determined by the standard procedures except for the specimens on which only MIP (Mercury Intrusion Porosimetry) determined values exist. The values determined by standard techniques on some duplicate specimens indicated that the dry densities calculated by the MIP technique are lower by about 0.05 kg/m$^3$, especially in the fresh to moderately decomposed granite specimens (Table 22). Possible sources of error in MIP-determined material properties are discussed by Ebuk (1990).

Linear relationships with significant correlations exist between $d_d$ and the indices WPI, $I_{mob}$, SA ratio and LOI. The specimen HG5D1 gave significant scatter from the observable trends. It was taken adjacent to a kaolinized patch in block sample HG5. This specimen has not been included in the statistical assessment of the data in Figures 17 and 18.

### 11.4 Classification of Weathering Grades of Granite in Terms of Dry Density and SPT Values

A classification of the material weathering grades in Hong Kong granites with respect to their dry densities is presented in Table 23 (see also Figures 17 and 18), based on the test results from Shouson Hill, Gamon (1986), and the author's own experience. The boundaries between the grades are approximate and they are chosen to include the majority of common granite types in the Territory. The table shows that subgrades of the highly decomposed and completely decomposed granites can be distinguished on the basis of their dry density values.

The relationship between dry density, void ratio and SPT N value for the soil grades of weathered granite is illustrated in Figure 19 for two different granite types. Also shown in the Figure is the curve drawn for the relationship between density/void ratio and SPT N1 value for a normally consolidated medium-grained sedimentary sand. The effect of bonding on the SPT value is apparent from Figure 19. The less weathered the rock the bigger the difference in SPT value between the bonded weathered material and the unbonded sandy soil which has a similar particle size distribution.

### 11.5 Schmidt Hammer Value

Schmidt hammer test is one of the quickest and simplest index tests used to characterize the degree of weathering (Hencher & Martin, 1982; Irfan & Powell, 1985) as well as for indirectly evaluating rock strength (Hucka, 1965; Dearman & Irfan, 1978). However, care needs to be taken in carrying out the test as the results are influenced by wetness of the surface, discontinuities and roughness of the surfaces, if carried out in the field. The test was also found to be useful in characterizing the weathered condition of the rock mass for determination of suitable founding depth of hand-dug piles in Hong Kong by Irfan & Powell (1985).

Table 24 gives a classification of the weathering grades of a coarse-grained granite in terms of Schmidt hammer values, based on an extensive field characterization carried out by Irfan & Cipullo (1988) on a slope along Ching Cheung Road, Kowloon. The tests were carefully carried out by the authors themselves using an N-type hammer, along freshly exposed chunam strips, to aid in identification and classification of material types on the slope.

The table also shows the Schmidt hammer values reported by Hencher & Martin (1982) for Hong Kong granites in general, by Irfan & Powell (1985) for Tai Po granodiorite, and Dearman & Irfan (1978) for weathered U.K. granites.

The ranges of values for each weathering grade are very similar for the coarse-grained granite and Tai Po granodiorite, whereas those reported by Hencher & Martin are generally much lower, particularly in the slightly decomposed and completely decomposed grades. The results for the completely decomposed granite from Ching Cheung Road indicate that it is possible to differentiate between various subgrades in this grade from the results of insitu Schmidt hammer tests.

## 11.6 Modified Degree of Decomposition Index

A modified degree of decomposition index (Irfan, 1988), $Xd_{mod}$, based on Lumb (1965) was determined for the soil grades of weathered granite from Shouson Hill and King's Park.

In the normal method of determining Xd, feldspars which normally occur in various states of decomposition are counted as 'feldspar'. This results in an erroneous count of the true unaltered feldspar content. Iron-oxide cementation of partially to wholly altered feldspar pseudomorphs may also affect the results, as observed with the completely decomposed specimens from King's Park. With these factors in mind, a modified technique of finger crushing of partially decomposed feldspars was adopted and $Xd_{mod}$ values were determined (Table 25). This gave a more accurate indication of the unaltered feldspar content of the soil grades and resulted in relatively higher Xd values than those reported by Lumb for Hong Kong decomposed granites (Irfan, 1988). Nevertheless, correlation between the values of $Xd_{mod}$ and the unaltered feldspar content (Table 12) is still poor (not shown).

It is considered that both the degree of decomposition index and the modified index determinations are inappropriate for fine-grained rocks, especially the volcanic rocks with a high content of cryptocrystalline or microcrystalline feldspar and quartz. The Xd determination is very time consuming and cumbersome even for coarse-grained granites. In addition, the index is not a very reliable indicator of feldspar decomposition, and it does not take into account the structural fabric elements such as voids and microcracks.

## 11.7 Micropetrographic Indices

A number of micropetrographic indices were determined from the results of the modal analysis, such as the percentages of altered and sound (unaltered) minerals, the percentage of microcracks and pores and the micropetrographic index, Ip. The micropetrographic index was calculated from the following formula :

$$Ip = \frac{\%\ \text{Sound Constituents}}{\%\ \text{Unsound Constituents}}$$

$$Ip = \frac{\%\ (\text{quartz} + \text{unaltered feldspar} + \text{unaltered biotite} + \text{others})}{\%\ (\text{altered feldspars} + \text{voids} + \text{microcracks})}$$

The results of the quantitative micropetrographic index determinations (Table 25) are in agreement with the qualitative fabric and mineralogical assessments described in Section 10, indicating that this technique can be used to characterize most of the fabric and mineralogical properties of the weathered coarse-grained igneous rocks including the specimens from the saprolitic and residual soil grades. Dearman & Irfan (1978) demonstrated that the results of micropetrographic indices are correlatable with physical and mechanical properties of granitic materials weathered to various stages, often as simple linear relationships. This correlation has not been attempted for Hong Kong granites.

### 11.8 Particle Size Distribution and Degree of Weathering

It is known that determination of particle size distribution of saprolitic and residual soils is sensitive to the test procedures used, e.g. use of pestle and mortar to crush soil, type of dispersing agent, amount of agitation (Gidigasu, 1975; Mitchell & Sitar, 1982; Massey et al, 1989).

Lumb (1962) reported large variations in grading for weathered granitic soils in Hong Kong, even occurring in the specimens taken from the same trial pit. This may be partly due to differences in pretreatment procedures. Indeed, particle size distribution obtained on some soil specimens from Shouson Hill using two different methods (one which involved the use of pestle and mortar in accordance with the standard method in the Public Works Central Laboratory and another which involved the use of pestle and mortar with additional finger crushing of soft feldspars) showed slight to significant variations in the clay and silt contents (Table 26).

The main reason for large variations in grain size in saprolitic and residual soils is the variation of these soils in terms of mineralogical composition and fabric resulting from different degrees of physical and chemical weathering, alteration and leaching conditions at each site. Figure 20 illustrates clearly the effect of weathering on the particle size distribution of a coarse-grained granite from Ching Cheung Road (data from Irfan & Cipullo, 1989). In addition to the weathering and alteration effects, variations in grain size of the soils are also due to variations in initial grain size of the original rock.

Results of particle size analyses on soils from Shouson Hill (Table 26) show that both clay and silt contents increase, in general, with increased weathering. The particle size distribution is also affected by the degree of alteration and other processes (e.g. leaching conditions). For example, altered specimens (e.g. sample HS3) have higher clay and silt contents and the disintegrated specimens have higher gravel contents.

The clay contents of the highly decomposed specimens are less than 2%, the completely decomposed specimens 2% to 9%, and the transition to residual soil specimens 7% to 18%. The clay contents of the altered King's Park specimens were also small, less than 16%, even when finger crushing method was used. Lumb (1962) also reported clay contents of less than 10% for decomposed granitic soils. However, the results of modal analysis and the mineral compositions calculated from XRD and chemical analysis (Table 16) indicate that the clay mineral contents of, for example, completely decomposed granite specimens from Shouson Hill, are in excess of 30% by weight. The specimens from King's Park have clay mineral contents of over 45%. Petrographic examination revealed that some mineral constituents, particularly alkali feldspars, are in various states of decomposition even within the same specimen. Clay minerals and other alteration products of clay size are therefore locked in, in partially altered grains, particularly in highly and completely decomposed specimens. Hence these clay minerals would not be dispersed unless rigorously broken down by mechanical means.

Another reason for obtaining lower than expected clay contents in particle size analysis of granitic saprolitic soils is that the majority of the clay minerals are silt size, usually in the range of 4 to 8 µm, as revealed by TEM and SEM studies (Section 10). The dominant mineral is the tubular halloysite, except in hydrothermally altered specimens in which kaolinite becomes dominant. In the residual soil specimens, the grain size of the clay minerals, which is now dominantly kaolinite, decreases but there is still a significant portion in fine silt size.

In the case of residual soil specimens, cementation or aggregation of clay minerals by sesquioxides (hydrated iron and aluminium oxides) appears to have influenced the particle size resulting in lower contents of clay size material than expected. Irfan (1986) also noted that specimens which were oven-dried at 105°C gave lower clay and silt contents when compared with air-dried specimens. This is probably the result of creation of a stronger bond between the particles upon dehydration of the sesquioxides. Drying is also accompanied by shrinkage which brings the particles closer together. This process takes place during air-drying, becoming more pronounced on oven-drying to high temperatures of 105°C or so (see Gidigasu, 1975 and Brenner et al, 1978).

## 12. EFFECTS OF MICROSTRUCTURE AND MINERALOGY ON BEHAVIOUR OF GRANITIC SOILS

The behaviour of saprolitic and residual granitic soils insitu and in the laboratory differ considerably from transported soils of similar particle size distribution and plasticity characteristics (Massey et al, 1989). This is due to their specific mineralogical and microstructural characteristics developed as a legacy of the weathering environment and other alteration processes as explained in Section 10. Therefore, the relationships which have been developed for transported soils, relating the results of classification tests and various engineering properties, do not seem to hold for these soils formed in tropical and subtropical regions (Vaughan, 1985). This is partly due to difficulties in determining a meaningful grain size for these soils, partly from the variability of grain size, voids and other products of weathering even within a particular sample, and also to a large extent from the presence of weak bonding and microfabric, either retained from the parent rock or generated during weathering (Irfan, 1988). In the less decomposed soil grades (e.g. highly decomposed and very dense completely decomposed granite), the relict primary bonding is strong enough to give a large true cohesion to the soil material.

The presence of fragile, partially decomposed or honeycombed minerals (mostly feldspars) makes these soils, in particularly the highly and completely decomposed granite materials, susceptible to severe breakdown by attrition during sieve analysis. Therefore, care is needed in every stage of sieve analysis (chemical treatment, oven-drying, sieving and sedimentation).

The granitic saprolitic and residual soils contain abundant halloysite. For example, up to 75% of the total clay mineral content and up to about 25% of the total rock is composed of halloysite in the completely decomposed granite grade (Section 10). Halloysite is a clay mineral with tubular structure. It occurs in two forms; metahalloysite (dehydrated form) and hydrated halloysite. The latter loses water of hydration on drying (Hughes, 1966). This occurs when the relative humidity falls below 50% or the temperature rises above 50°C (Geological Society of London, 1990). The loss of hydration in a pure halloysite is equal to 14% of the dry soil weight.

The water in the structure of hydrated halloysite is inert and does not influence the mechanical behaviour of the soil. However, if the sample is dried above 50°C, this water is driven out resulting in erroneous moisture content determination for the sample. Also, the tubular structure collapses, breaking the mineral into plates of kaolinite which are of smaller grain size.

The proportion of hydrated halloysite present in the samples used for the study has not been determined since it is difficult to distinguish between the two forms of halloysite from XRD analysis without special procedures (See Irfan, 1994b).

The granitic saprolitic and residual soils contain some goethite, up to about 5% of the total weight, and a minor amount of gibbsite. A small amount of hematite may also be present. These minerals are collectively known as sesquioxides of iron and aluminum. The physical and engineering properties of tropical and saprolitic soils can be greatly influenced by the presence of sesquioxide minerals, particularly when these occur in significant quantities (Mitchel & Sitar, 1982; Gidigusu, 1975). They coat the surfaces of individual soil particles, binding them into clusters and aggregations. The coating reduces the ability of clay minerals to absorb water and can also physically cement adjacent grains, thus giving a true cohesion to the soil, particularly in the residual soil stage. Both effects reduce plasticity, but intensive remoulding of the soil in the laboratory breaks down aggregates and sesquioxide coatings, with an attendant increase in plasticity (Geological Society of London, 1990). This has important bearing in the expected behaviour of soil used as fill since the plasticity of the material placed in the field may be lower than indicated by the standard laboratory tests on remoulded samples. Sesquioxides also lose their water of hydration and become less plastic when dried at 105°C (Geological Society of London, 1990). Again, this water normally takes no part in the mechanical behaviour of the material, but is reflected in the results of tests undertaken to temperate standards of a higher moisture content. Oven-drying therefore affects the results of particle size analysis and subsequently the Atterberg Limit determinations.

Knill & Best (1970) reported that a saprolitic fill material in Hong Kong containing goethite, developed bonding quite quickly by re-cementation after placement. This may make the fill material brittle and prone to cracking if subjected to subsequent deformations.

The interaction of sesquioxides with clay silicates and other materials in the soil environment is not well understood (Schwertmann, 1987a, b). Further work is required in this field.

For more details on the effects of mineralogy and fabric of these soils on the results of classification tests and engineering behaviour, reference should be made to Gidigasu (1975), Vaughan (1985, 1988), Vaughan et al (1988) and Geological Society of London (1990) for a general treatment, and to Irfan (1988) and Massey et al (1989) for granites in Hong Kong.

## 13. CONCLUSIONS

Although chemical weathering has been the dominant process, hydrothermal alteration and tectonic processes much predating weathering, have also been important in profile development and soil formation in igneous rocks of Hong Kong.

The residual soil zone (or grade) is not well developed in Hong Kong, usually less than a few metres thick, in comparison to those found in the humid tropical regions. The residual soil zone in granites may be underlain by a transitional soil zone, which may be up to 6 m thick at some locations, before the completely weathered rock mass or saprolitic soil zone is reached.

The recent classification scheme proposed by Wesley and Irfan (1994), which groups the soils on the basis of common engineering properties based on the mineralogical and structural characteristics appears to be more suitable than the scheme proposed by the Geotechnical Society of London (1990) for classifying the soils formed from weathering of granitic rocks as well as other rocks. This scheme can be used as a supplement to the general mass weathering scheme adopted for the grouping and subdivision of the soil zones for engineering purposes.

The six-fold material weathering grade scheme, based on GCO (1988) but with further subdivisions and refinements that are proposed in this document can be used to describe and classify the weathered granitic materials within each broad soil group or rock mass zone. In this respect, for example, the 'CDG' as defined in GCO (1988) has been subdivided into a number subgrades based on degree and type of weathering and alteration or relative density (or strength). Each material type within the CDG grade can have significantly different properties, e.g. shear strength, as demonstrated by Massey et al (1989).

With the exception of lixiviation index and alumina to calcium - and sodium-oxide ratio, many chemical indices have been found to be good indicators of the degree of chemical weathering for Hong Kong granites. The new Mobiles Index proposed in this document has been found to be a useful index for the characterization of degree of weathering in granites, particularly in reasonably well-drained conditions such as those found in most hilltops and hillsides in Hong Kong.

The results of the quantitative micropetrographic index determination are in agreement with the qualitative fabric and mineralogical determinations, indicating that this index can be used to characterise most of the fabric elements of weathered granites including the soil grades. The relationships between various indices and physical and mechanical properties have not been determined for Hong Kong granites, but such correlations exist for weathered granites elsewhere. The degree of decomposition index of Lumb (1965), which is cumbersome to determine, has been found to be an unreliable indicator of degree of weathering of granites.

As far as the indices determined from the physical tests are concerned, the dry density and to some extent the Schmidt hammer test values have been found to be good measures of degree of weathering in granites, including the subgrades within the completely decomposed grade. However, caution is needed in carrying out the Schmidt hammer test.

A relationship has been derived between field-determined SPT value and laboratory-determined dry density/void ratio for the soil grades and subgrades. This relationship can be used, with caution (e.g. reliable SPT determinations are necessary), to determine the material type from SPT results or vice versa or for zoning/mapping purposes.

Large variations in the grain size of saprolitic and residual soils reported in the literature are partly due to differences in pretreatment techniques. However, the main reason is the variation in the mineralogical composition, fabric and bonding characteristics of specimens resulting from different degrees of physical and chemical weathering, hydrothermal alteration and leaching conditions.

A mineralogy and fabric model for granite weathering in Hong Kong has been established, particularly applicable to hilltop and hillside environments. Mineralogy and fabric changes occurring in valley bottoms and other poorly-drained environments have not been documented due to non-availability of data. However, it is considered that the model is also generally applicable to weathered granite in these environments, with possible formation of minor amounts of non-kaolinitic clay minerals and less solution effects. It is emphasized that the weathering effects are progressive and rapid variations in material grades and subgrades can occur laterally as well as vertically in many sites.

The presence of halloysite and sesquioxide minerals and the specific microstructure developed in the soil grades of granite, require that special precautions are taken in the preparation of specimens for conventional laboratory testing and the interpretation of the test results. Reference should be made to recently published literature on these topics (e.g. Geological Society of London, 1990; Vaughan 1988; Irfan, 1988; Massey et al, 1989).

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# LIST OF TABLES

Table 1 - Chemical Composition of Granitoid Rocks in Hong Kong in Terms of Major Oxides (Weight %)
(after Addison, 1986 and Sewell & Langford, 1991)

| Major Oxides | Granodiorite | | Granites | | | | | | | | | | | Syenite | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Coarse-grained | | | | Medium-grained | | | Fine-grained | | | | | |
| Sample | 8743 | 9 | 8511 | 9747 | 8002 | 10119 | 8703 | 8709 | 8721 | 8710 | 8717 | 8724 | 219 | 8683 | 200 |
| $SiO_2$ | 66.21 | 70.31 | 72.35 | 75.65 | 73.04 | 72.46 | 72.96 | 76.61 | 77.42 | 75.92 | 76.75 | 75.68 | 75.95 | 67.40 | 65.64 |
| $TiO_2$ | 0.72 | 0.47 | 0.29 | 0.08 | 0.22 | 0.34 | 0.25 | 0.13 | 0.06 | 0.16 | 0.02 | 0.06 | 0.03 | 0.33 | 0.33 |
| $Al_2O_3$ | 14.43 | 13.63 | 13.45 | 12.57 | 13.14 | 13.36 | 13.26 | 12.01 | 11.81 | 12.03 | 12.23 | 12.94 | 12.86 | 15.52 | 16.42 |
| $Fe_2O_3$* | 5.29 | 0.68 | 0.27 | 1.38 | 0.48 | 2.60 | 2.41 | 1.48 | 0.99 | 1.59 | 0.84 | 1.02 | 0.09 | 3.31 | 1.57 |
| FeO | * | 2.60 | * | * | * | * | * | * | * | * | * | * | 0.77 | * | 1.50 |
| MnO | 0.10 | 0.09 | 0.04 | 0.04 | 0.04 | 0.11 | 0.09 | 0.06 | 0.08 | 0.04 | 0.04 | 0.05 | 0.06 | 0.12 | 0.13 |
| MgO | 1.59 | 0.92 | 0.36 | 0.04 | 0.37 | 0.54 | 0.33 | 0.07 | 0.00 | 0.15 | 0.00 | 0.00 | 0.01 | 0.43 | 0.60 |
| CaO | 3.23 | 1.24 | 1.99 | 0.99 | 1.54 | 2.14 | 1.34 | 0.89 | 0.72 | 0.90 | 0.49 | 0.71 | 0.62 | 1.59 | 1.38 |
| $Na_2O$ | 3.10 | 3.33 | 2.56 | 3.12 | 3.20 | 3.16 | 3.40 | 3.16 | 3.61 | 3.37 | 4.05 | 3.98 | 3.98 | 3.74 | 3.66 |
| $K_2O$ | 3.98 | 4.52 | 5.21 | 5.32 | 4.94 | 4.48 | 5.33 | 5.25 | 4.85 | 5.27 | 4.94 | 5.29 | 4.81 | 6.81 | 7.23 |
| $P_2O_5$ | 0.18 | 0.17 | 0.06 | 0.01 | 0.07 | 0.07 | 0.05 | 0.00 | 0.00 | 0.02 | 0.00 | 0.00 | 0.01 | 0.06 | 0.11 |
| LOI | 0.93 | 1.28 | 0.63 | 0.48 | - | 0.45 | 0.33 | 0.13 | 0.48 | 0.45 | 0.45 | 0.35 | 0.77 | 0.40 | 1.03 |
| Total | 98.17 | 99.37 | 99.64 | 99.68 | 98.66 | 99.71 | 99.75 | 99.79 | 100.02 | 99.90 | 99.81 | 100.08 | 99.48 | 99.71 | 100.02 |

* Included in $Fe_2O_3$ content.

Locations :

| | | | |
|---|---|---|---|
| 9 | Nam Hang borrow area, Tai Po | 8721 | Stanley Pluton |
| 8743 | North Tsing Yi | 8710 | Chi Ma Wan Pluton |
| 8511 | Tai Lam Pluton | 8717 | Mt Butler Pluton |
| 9747 | Tsing Shan Pluton | 8724 | Kwun Tong Pluton |
| 8002 | Sung Kong Pluton, Kau Yi Chau | 219 | Shatin Pluton, Shek Lei Quarry |
| 10119 | Sung Kong Pluton, Pak Kok, Lamma | 8683 | D'Aguilar Syenite, Cape D'Aguilar |
| 8703 | Kowloon Pluton, Ko Shan | 200 | Ngong Ping Shan, Sha Tin |
| 8709 | Kowloon Pluton, Pak Tin Estate | | |

Table 2 - A Simple Summary of Weathering Processes (Sheet 1 of 2)

| Mechanical Weathering Processes | | Chemical Weathering Processes | |
|---|---|---|---|
| MECHANICAL UNLOADING (Exfoliation) | Vertical expansion due to the reduction of vertical load by erosion. This will open existing fractures and may permit the creation of new fractures. | SOLUTION | Dissociation of minerals into ions, greatly aided by the presence of $CO_2$ in the soil profile, which forms carbonic acid ($H_2CO_3$) with percolating rainwater. |
| MECHANICAL LOADING | Impact on rock, and abrasion, by sand and silt size windborne particles in deserts. Impact on soil and weak rocks by rain drops during intense rainfall storms. | OXIDATION | The combination of oxygen with a mineral to form oxides and hydroxides or any other reaction in which the oxidation number of the oxidized elements is increased. |
| THERMAL LOADING (Heating and Cooling; Freeze and Thaw) | Expansion by the freezing of water in pores and fractures in cold regions, or by the heating of rocks in hot regions. Contraction by the cooling of rocks and soils in cold regions. | REDUCTION | The release of oxygen from a mineral to its surrounding environment: ions leave the mineral structure as the oxidation number of the reduced elements is decreased. |
| WETTING AND DRYING | Expansion and contraction associated with the repeated absorption and loss of water molecules from mineral surfaces and structures: (see HYDRATION). | HYDRATION | Absorption of water molecules into the mineral structure. Note: this normally results in expansion, some clays expand as much as 60%, and by admitting water hasten the processes of solution, oxidation, reduction and hydrolysis. |

Table 2 - A Simple Summary of Weathering Processes (Sheet 2 of 2)

| Mechanical Weathering Processes | | Chemical Weathering Processes | |
|---|---|---|---|
| CRYSTALLIZATION (Salt Crystal Growth) | Expansion of pores and fissures by crystallization within them of minerals that were originally in solution. Note expansion is only severe when crystallization occurs within a confined space. | HYDROLYSIS | Hydrogen ions in percolating water replace mineral cations: no oxidation-reduction occurs. |
| PNEUMATIC LOADING | The repeated loading by waves of air trapped at the head of fractures exposed in the wave zone of a sea cliff. | LEACHING | The migration of ions produced by the above processes. Note: the mobility of ions depends upon their ionic potential: Ca, Mg, Na, K are easily leached by moving water, Fe is more resistant, Si is difficult to leach and Al is almost immobile. |
| | | CATION EXCHANGE | Absorption onto the surface of negatively charged clay of positively charged cations in solution, especially Ca, H, K, Mg. |

## Table 3 - Idealised Weathering Profiles in Igneous Rocks and a Comparison of Various Engineering and Geological Classification Schemes

| Description of States of Weathering of Rock Mass (BS 5930 : 1981) | Dearman (1976)* BSI (1981)* All Rocks | IAEG (1980)* All Rocks | Ruxton & Berry, (1957) Corestone-bearing Granites | Deere & Patton, (1971) Igneous & Metamorphic Rocks | | GCO (1984) Igneous & Volcanic Rocks | GCO (1988) Corestone-bearing Igneous Rocks | | Geol Soc. (1990)* All Rocks | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Soil | | | Soil | | | | | Humus | |
| All rock material converted to soil : mass structure and material fabric destroyed. Significant change in volume | VI Residual Soil | VI Residual Soil | Zone A -- Horizon<br>B -- Horizon | I Residual Soil (Saprolite) | IA<br>IB | Zone A | Residual Soil | RS | Residual Soil | VI |
| All rock material decomposed and/or disintegrated to soil. Original mass structure still largely intact | V Completely Weathered | V Extremely Weathered | I Residual Debris<br>IIA Residual | | IC | Zone B | Partially Weathered Rock | PW 0/30 (< 30% Rock) | | V |
| More than 50% of rock material decomposed and/or disintegrated to soil. Fresh/discoloured rock present as discontinuous framework or corestones | IV Highly Weathered | IV Highly Weathered | IIB Debris with Corestones (0 - 50% rock) | II Transition from Saprolite to Partly Weathered Rock | IIA | | | PW 30/50 | | IV |
| Less than 50% of rock material decomposed and/or disintegrated to soil. Fresh/discoloured rock present as continuous framework or corestones | III Moderately Weathered | III Moderately Weathered (< 35% Soil) | III Corestones with Residual Soil (50 - 90% rock) | | | Zone C | | PW 50/90 | Weathered Bedrock | III |
| Discoloration indicates weathering of rock material and discontinuity surfaces. All rock material may be discoloured by weathering and may be weaker than in its fresh condition | II Slightly Weathered | II Slightly Weathered | IV Partially Weathered Rock | Partly Weathered Rock | IIB | Zone D | | PW 90/100 | | II |
| No visible sign of rock material weathering, perhaps slight staining of major discontinuity surfaces | I Fresh | I Fresh | Bedrock | III Unweathered Rock | III | | Unweathered Rock | UW | Unweathered Bedrock | I |

Legend :

* Scales of weathering grades of rock mass. Grades do not necessarily occur in the sequence indicated.

Table 4 - Classification of Tropical Residual Soils
(Geological Society of London, 1990)

FRESH (UNWEATHERED) BEDROCK

TROPICAL WEATHERING

| ENGINEERING WEATHERING GRADES | EXPLANATORY TERMS | ADOPTED TERMINOLOGY |
|---|---|---|
| VI Residual Soil | Solum | TROPICAL RESIDUAL SOIL |
| V Completely Weathered | Saprolite | |
| IV Highly Weathered | | |
| III Moderately Weathered | Weathered Bedrock | |
| II Slightly Weathered | | |
| I Fresh | Bedrock | |

Extensive weathering within these zones causes major mineralogical changes associated with processes of solution, transportation in solution and precipitation (Pedogenetic transformation)

| ADOPTED PEDOLOGICAL CLASSIFICATION (DUCHAUFOUR, 1982) | |
|---|---|
| FERSIALLITIC SOILS | increasing intensity of weathering ↓ |
| FERRUGINOUS SOILS | |
| Ferrisols (transitional) | |
| FERRALLITIC SOILS | |

Table 5 - Classification and Characteristics of Saprolitic and Residual Soil Groups (after Wesley & Irfan, 1994)

| GROUP | | EXAMPLES | MEANS OF IDENTIFICATION | COMMENTS ON LIKELY ENGINEERING PROPERTIES AND BEHAVIOUR |
|---|---|---|---|---|
| MAJOR GROUP | SUB GROUP | | | |
| GROUP A | (a) Strong macro-structure influence | Highly weathered rocks from acidic or intermediate igneous rocks, and sedimentary rocks. | General appearance | This is a very large group of soils (including the "saprolites") where behaviour (especially in slopes) is dominated by the influence of the discontinuities, fissures etc. |
| | (b) Strong micro-structure influence | Completely weathered rocks formed from igneous and sedimentary rocks. | General appearance and evaluation of sensitivity, liquidity index etc. | These soils are essentially homogeneous and form a tidy group much more amenable to systematic evaluation and analysis than group (a) above. Identification of nature and role of bonding (from relict primary bonds to weak secondary bonds) important to understanding behaviour. |
| | (c) Little structural influence | Soils formed from very homogeneous rocks. | Little or no sensitivity, uniform appearance. | This is a relatively minor sub-group. Likely to behave similarly to moderately overconsolidated soils. |
| GROUP B | (a) Smectite (montmo-rillonite) group | Black cotton soils, many soils formed in tropical areas in poorly drained conditions. | Dark colour (grey to black) and high plasticity suggest soils of this group. | These are normally problem soils found in flat or low lying areas, of low strength, high compressibility, and high swelling and shrinkage characteristics. |
| | (b) Other minerals | | | This is likely to be a very minor sub-group. |
| GROUP C | (a) Allophane group | Soils weathered from volcanic ash in the wet tropics and in temperate climates | Very high natural water contents, and irreversible changes on drying | These are characterised by very high natural water contents, and high liquid and plastic limits. Engineering properties are generally good, though in some cases high sensitivity could make handling and compaction difficult. |
| | (b) Halloysite group | Soils largely derived from older volcanic rocks; especially tropical red clays. | Reddish colour, well drained topography and volcanic parent rock are useful indicators | These are generally very fine grained soils, of low to medium plasticity, but low activity. Engineering properties generally good. (Note that there is often some overlap between allophane and halloysitic soils). |
| | (c) Sesquioxide | The soil group loosely referred to as "lateritic", or laterite | Granular, or nodular appearance | This is a very wide group, ranging from silty clay to coarse sand and gravel. Behaviour may range from low plasticity silty clay to non-plastic gravel. |

Table 6 - Examples of Index Tests Used to Assess Degree of Weathering in Igneous Rocks

| Technique | Index | Reference | Weathering Range Applied |
|---|---|---|---|
| Chemical Analysis, DTA | Weathering Potential Index | Reiche, 1943 | A-D? |
| | Weathering Product Index | Reiche, 1943 | A-D? |
| | Silica-to-Alumina Ratio | Ruxton, 1968 | A-D? |
| | Lixiviation Index (β) | Rocha Filho et al, 1985 | C-D |
| | Sesquoxide Content | | C-D |
| | Alumina to Calcium-Sodium Oxide ratio | Harnois & Moore, 1988 | A-C? |
| | Alumina to Potassium-Sodium Oxide ratio | | A-C? |
| | pH of Soil | Matsuo et al, 1968 | C-D |
| | Abrasion pH of Feldspars | Malomo, 1980 | |
| | Ignition ($H_2O^+$) Loss | Suoeka et al, 1985 | A-C |
| | Specific Gravity of Feldspars | Matsuo & Nishida, 1968 | C-D |
| | Mobiles Index | (This paper) | A-C |
| Optical Microscope | Decomposition Index ($X_d$) | Lumb, 1965 | A-C |
| | Micropetrographic Index ($I_p$) | Irfan & Dearman, 1978a<br>Dearman & Irfan, 1978 | A-C<br>A-C |
| | Micropetrographic Fracture Index ($I_f$) | Irfan & Dearman, 1978a | A-C |
| | % Secondary Minerals | Weinert, 1964 | A-C |
| Physical Tests (non-standard tests) | Breaking of Core or Lumps of Soil | Moye, 1955<br>Hencher & Martin, 1982 | B-C<br>B-C |
| | Feldspar Grittiness Index | Irfan & Dearman, 1978b<br>Geological Society, 1990 | A-D<br>A-D |
| | Slakeability | Moye, 1955<br>Irfan & Dearman, 1978b<br>Hencher & Martin, 1982 | C<br>C-D<br>C |
| | Decomposition Index | Weinert, 1964 | A-D |
| Mechanical and Physical Tests (Standard laboratory or field tests) | Quick Absorption Index | Hamrol, 1961<br>Irfan & Dearman, 1978b<br>Dearman & Irfan, 1978 | A-C<br>A-C<br>A-C |
| | Dry Density | Uriel & Dapena, 1978<br>Irfan & Dearman, 1978b<br>Dearman & Irfan, 1978 | A-B<br>A-C<br>A-C |
| | Velocity Index | Iliev, 1967<br>Dearman & Irfan, 1978 | A-C<br>A-C |
| | Schmidt Hammer Value | Dearman & Irfan, 1978<br>Hencher & Martin, 1982<br>Irfan & Powell, 1985<br>GCO, 1988 | A-C<br>B-C<br>A-C<br>C-D |
| | Hand Penetrometer | Hencher & Martin, 1982 | C-D |
| | Residual Bond Strength | Ebuk et al, 1990 | C |

A - Fresh Rock, B - Slightly/Moderately Decomposed/Disintegrated,
C - Highly/Completely Decomposed/Disintegrated,
D - Residual Soil.

Table 7 - Terms for Describing Degree of Decomposition of Feldspars (After Irfan, 1988)

| Degree of Decomposition | Grittiness Term | Scale | Description |
|---|---|---|---|
| Fresh to Slightly | Hard | 1 | Cannot be cut by knife; cannot be grooved with a pin. |
| Moderately | Gritty | 2 | Can be cut by knife or grooved with a pin under heavy pressure. |
| Highly | Powdery | 3 | Can be crushed to silt sized fragments by finger pressure. |
| Completely | Soft | 4 | Can be moulded very easily with finger pressure. |

Table 8 - Mineralogical Composition of Fresh Granite, Shouson Hill and King's Park

| Location | Sample No. | Feldspars | Quartz | Biotite | Others |
|---|---|---|---|---|---|
| Shouson Hill | - | 70.7 | 28.2 | 1.0 | 0.1 |
| | GHG1 | 57.4 | 40.6 | 2.0 | 0.0 |
| | 404.01 | 60.0 | 37.4 | 2.3 | 0.2 |
| | Mean | 62.7 | 35.4 | 1.8 | 0.1 |
| King's Park | KP01 | 55.8 | 37.0 | 6.7 | 0.5 |
| | KP02 | 52.2 | 35.8 | 11.4 | 0.4 |
| | Mean | 54.0 | 36.4 | 9.1 | 0.5 |

Note : Mineralogical composition of fresh granite is recalculated from Tables 12 and 13, by incorporating altered feldspars into feldspars, altered biotite into biotite and ignoring microcracks.

Table 9 - Chemical Analyses of Weathered Granite, Shouson Hill (Results from Hencher, 1990)

| Description | | Sample No. | Weight (%) | | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$[1] | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ | LOI | |
| Slightly Decomposed | | HG2 | 76.13 | 0.09 | 12.72 | 0.75 | 0.03 | 0.01 | 0.72 | 3.13 | 5.39 | 0.06 | 0.38 | 100.59 |
| Moderately Decomposed | | HG3 | 75.81 | 0.09 | 12.29 | 0.82 | 0.03 | 0.00 | 0.48 | 2.74 | 5.19 | 0.07 | 0.76 | 98.28 |
| Highly Decomposed | (M. Weak) | HG4S | 75.30 | 0.12 | 13.20 | 1.58 | 0.05 | 0.04 | 0.16 | 1.82 | 5.71 | 0.06 | 1.67 | 99.71 |
| | (Weak) | HG4 | 75.37 | 0.11 | 14.62 | 1.16 | 0.03 | 0.01 | 0.00 | 0.00 | 5.90 | 0.02 | 3.73 | 100.59 |
| | (V. Weak) | HG4W | 75.71 | 0.09 | 14.44 | 1.59 | 0.04 | 0.01 | 0.01 | 0.03 | 4.58 | 0.06 | 3.41 | 99.97 |
| Completely Decomposed | (V. Dense) | HG5D2 | 78.75 | 0.08 | 12.25 | 1.64 | 0.07 | 0.01 | 0.00 | 0.00 | 4.27 | 0.01 | 3.36 | 100.44 |
| | (Dense[2]) | HG5D1 | 62.31 | 0.13 | 22.77 | 2.03 | 0.10 | 0.00 | 0.00 | 0.16 | 5.84 | 0.06 | 6.06 | 99.46 |
| | (Loose) | HG5L | 74.21 | 0.19 | 16.49 | 2.01 | 0.03 | 0.00 | 0.01 | 0.00 | 1.30 | 0.06 | 5.81 | 100.10 |
| Residual Soil | | HG6 | 72.90 | 0.14 | 17.27 | 2.24 | 0.02 | 0.00 | 0.00 | 0.00 | 0.55 | 0.06 | 6.58 | 99.76 |

Notes : 1. As total iron-oxide content.
2. Also affected by hydrothermal alteration.
LOI = Loss on ignition.

Table 10 - Chemical Analyses of Weathered Granite, Shouson Hill (Results from Awoleye, 1991)

| Description | | Sample No. | Weight (%) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$[1] | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ | LOI |
| Fresh | (Core of a large corestone) | 404.01 | 76.85 | 0.13 | 11.74 | 1.59 | 0.08 | 0.28 | 0.85 | 3.08 | 5.53 | 0.02 | n.d. |
| Slightly Decomposed | (Moderately discoloured) | 404.02 | 77.70 | 0.12 | 11.85 | 1.27 | 0.03 | 0.28 | 0.27 | 2.92 | 5.05 | 0.02 | n.d. |
| Moderately Decomposed | (Moderately strong) | 404.03 | 77.61 | 0.12 | 11.98 | 1.41 | 0.08 | 0.23 | 0.63 | 2.98 | 5.07 | 0.02 | n.d. |
| Highly Decomposed | (Moderately weak) | 404.04 | 77.60 | 0.12 | 11.78 | 1.32 | 0.08 | 0.23 | 0.63 | 2.95 | 5.10 | 0.02 | n.d. |
| Completely Decomposed | (Decomposed) | 404.05 | 75.44 | 0.12 | 15.58 | 2.28 | 0.06 | 0.28 | 0.00 | 0.66 | 5.54 | 0.02 | n.d. |
| | (Altered) | 404.06 | 75.16 | 0.13 | 12.12 | 2.20 | 0.06 | 0.25 | 0.00 | 0.44 | 5.45 | 0.01 | n.d. |
| | (Disintegrated) | 404.07 | 75.18 | 0.15 | 16.16 | 2.18 | 0.08 | 0.18 | 0.00 | 0.40 | 5.32 | 0.01 | n.d. |
| Residual Soil | | 404.08 | 75.24 | 0.08 | 20.86 | 2.41 | 0.02 | 0.18 | 0.00 | 0.00 | 0.76 | 0.03 | n.d. |

Notes : 1. As total iron-oxide content
n.d. Not determined.

Table 11 - Chemical Variation in the Soil Grades of Weathered Granite, Shouson Hill and King's Park

| Description | | Sample No | Depth (m) | Weight, % | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ | LOI |
| Highly Decomposed | (Weak rock) | HG4 | 12.0 | 75.37 | 0.11 | 14.62 | 1.16 | 0.03 | 0.01 | 0.00 | 0.00 | 5.90 | 0.02 | 3.37 |
| | (V. weak rock) | HG4W | 11.5 | 75.71 | 0.09 | 14.44 | 1.59 | 0.04 | 0.01 | 0.01 | 0.03 | 4.58 | 0.06 | 3.41 |
| Completely Decomposed/ Disintegrated | (V. dense) | HG5D2 | 10.0 | 78.75 | 0.08 | 12.25 | 1.64 | 0.07 | 0.01 | 0.00 | 0.00 | 4.27 | 0.01 | 3.36 |
| | (Loose) | HG5L | 1.2 | 74.21 | 0.19 | 16.49 | 2.10 | 0.02 | 0.00 | 0.01 | 0.00 | 1.30 | 0.06 | 5.81 |
| | (Loose) | SH8 | 2.7 | 71.30 | 0.18 | 15.80 | 1.73 | 0.04 | 0.11 | 0.03 | 0.17 | 2.56 | 0.03 | 7.30 |
| | (Loose) | SH6 | 2.3 | 71.10 | 0.17 | 15.90 | 2.58 | 0.14 | 0.12 | 0.05 | 0.16 | 1.78 | 0.05 | 7.40 |
| | (Loose, altered) | SH5 | 2.0 | 71.80 | 0.18 | 16.80 | 1.34 | 0.10 | 0.08 | 0.02 | 0.09 | 2.22 | 0.05 | 6.30 |
| Transition Soil | (Small fabric loss) | SH7 | 2.1 | 69.50 | 0.17 | 16.90 | 1.28 | 0.03 | 0.12 | 0.06 | 0.15 | 2.86 | 0.02 | 8.00 |
| | (Large fabric loss) | SH3 | 0.9 | 73.20 | 0.17 | 16.00 | 1.57 | 0.02 | 0.08 | 0.02 | 0.06 | 1.00 | 0.03 | 6.65 |
| Residual Soil | | HG6 | 0.7 | 72.90 | 0.14 | 17.27 | 2.44 | 0.02 | 0.00 | 0.01 | 0.00 | 0.55 | 0.06 | 6.58 |
| Completely Decomposed | (Dense) | H1 | ? | 72.20 | 0.10 | 15.20 | 1.55 | 0.09 | 0.10 | 0.02 | 0.09 | 3.26 | 0.05 | 5.75 |
| Completely Decomposed | (altered) | KP2 | 1.0 | 67.10 | 0.34 | 18.70 | 2.80 | 0.05 | 0.08 | 0.09 | 0.01 | 0.35 | 0.05 | 9.85 |
| | (altered) | KP1 | 1.0 | 66.70 | 0.36 | 18.70 | 2.94 | 0.05 | 0.04 | 0.07 | 0.03 | 0.33 | 0.04 | 9.50 |

Table 12 - Quantitative Micropetrographic Analyses of Weathered Granite, Shouson Hill

| Description | | Sample No | Fresh Feldspars | Altered Feldspars | Quartz | Biotite | Altered Biotite | Others | Cracks Pores |
|---|---|---|---|---|---|---|---|---|---|
| "Fresh" Granite | | - | 68.2 | 2.0 | 28.1 | 0.7 | 0.3 | 0.1 | 0.6 |
| | | GHG1 | 53.9 | 3.2 | 40.4 | 1.3 | 0.7 | 0.0 | 0.5 |
| | | 404.01 | 56.8 | 3.0 | 37.3 | 1.7 | 0.6 | 0.2 | 0.4 |
| Slightly Decomposed | (Fresh core) | GHG2(SHS12) | 63.6 | 5.1 | 27.0 | 2.6 | 0.8 | 0.2 | 0.5 |
| | (Unstained) | 404.02 | 40.5 | 6.4 | 50.6 | 0.8 | 0.6 | 0.1 | 1.1 |
| | (Stained rim) | 404.02 | 38.8 | 8.3 | 41.4 | 6.6 | 1.4 | 0.1 | 3.1 |
| Moderately Decomposed | (Strong) | GHG3(SHS11) | 50.1 | 8.5 | 38.1 | 0.0 | 0.8 | 0.0 | 2.4 |
| | (Mod. strong) | 404.03 | 65.0 | 6.0 | 20.3 | 4.7 | 1.0 | 0.0 | 2.8 |
| | (Mod. strong) | GHG4(SHS10) | 48.3 | 10.1 | 35.6 | 0.4 | 2.5 | 0.1 | 3.0 |
| Highly Decomposed | (Mod. weak) | HG4S(SHS8) | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| | (Very weak) | GHG5(SHS6) | 28.1 | 31.2 | 16.6 | 1.4 | 6.8 | 0.3 | 15.6 |
| Completely Decomposed | (Very dense) | GHG6(SHS5) | 26.7 | 23.7 | 28.0 | 0.0 | 5.8 | 0.0 | 15.6 |
| | (Dense) | 404.05 | 27.5 | 27.8 | 20.5 | 1.3 | 4.1 | 0.1 | 18.5 |
| | (Dense) | SH8 | 10.2 | 40.5 | 24.3 | 0.1 | 1.9 | 0.1 | 22.9 |
| | (Dense) | SH6 | 9.4 | 41.4 | 21.5 | 0.8 | 3.0 | 0.0 | 23.7 |
| | (Loose, slightly altered) | 404.06 | 13.7 | 36.6 | 24.0 | 0.1 | 1.6 | 0.0 | 24.0 |
| | (Dense, altered) | SH5a | 7.3 | 46.5 | 21.4 | 0.1 | 2.3 | 0.0 | 22.3 |
| | (Loose, disintegrated) | 404.07 | 20.7 | 32.0 | 7.3 | 0.1 | 1.7 | 0.0 | 38.0 |
| Transition Soil | Small fabric loss | SH7 | 9.8 | 47.0 | 15.0 | 0.0 | 3.1 | 0.1 | 24.8 |
| | Large fabric loss | SH3 | 2.7 | 55.6 | 25.2 | 0.0 | 3.0 | 0.0 | 13.5 |
| Residual Soil | | 404.08 | 2.8 | 58.8[1] | 24.1 | 0.0 | 0.8 | 0.0 | 13.2[2] |
| | | GHG7(SHS1) | 1.5 | 54.3[1] | 27.5 | 0.0 | 2.0 | 0.0 | 14.5[2] |

Notes : 1. Includes all clay minerals including those filling microcracks.
2. Unfilled microcracks and pores only.

Table 13 - Quantitative Micropetrographic Analyses of Weathered Granites, King's Park and Homantin

| Description | Sample No | Fresh Feldspars | Altered Feldspars | Quartz | Biotite | Altered Biotite, | Others[1] | Cracks, Pores |
|---|---|---|---|---|---|---|---|---|
| Fresh Granite (Core of corestone) | KP01 | 53.1 | 2.3 | 36.7 | 6.0 | 0.7 | 0.5 | 0.7 |
| | KP02 | 47.1 | 4.6 | 35.4 | 10.5 | 0.8 | 0.6 | 1.0 |
| Completely Decomposed (Altered) | KP2 | 1.8 | 45.6 | 23.0 | 0.0 | 11.9 | 0.1 | 17.6 |
| (Altered) | KP1 | 1.7 | 49.3 | 18.4 | 0.1 | 6.6 | 0.2 | 23.7 |
| Completely Decomposed (Dense) | H1 | 12.0 | 37.0 | 22.5 | 0.2 | 5.5 | 0.1 | 22.6 |

Note : 1. Mostly magnetite with some sphene

Table 14 - Semi-quantitative Mineralogical Composition of Weathered Granite by XRD, Shouson Hill (Results from LCPC)

| Description | Sample No | Feldspars $P_f$ | Feldspars $K_f$ | Quartz | Micas | Kaolin Minerals | Chlorite | Iron-Oxides | Gibbsite | Amphibole? |
|---|---|---|---|---|---|---|---|---|---|---|
| Fresh Granite | GHG1 | ++++ | ++++ | ++++ | ++ | - | ++ | - | - | |
| Slightly Decomposed | GHG2 | ++++ | ++++ | ++++ | + | - | - | - | - | tr? |
| Moderately Decomposed | GHG3 | ++++ | ++++ | ++++ | + | - | - | - | - | |
| | GHG4 | ++++ | ++++ | ++++ | + | - | + | - | - | |
| Highly Decomposed | GHG5 | - | ++++ | ++++ | + | ++ | - | - | - | |
| Completely Decomposed | GHG6 | - | ++++ | ++++ | + | ++ | - | - | - | |
| Residual Soil | GHG7 | - | + | ++++ | + | ++++ | + | +(G) | + | +? |

Legend : G - Goethite, $P_f$ - Plagioclase feldspar, $K_f$ - Alkali feldspar.
Dominance scale (as given by Laboratoire Central des Ponts et Chaussées)

| | | | |
|---|---|---|---|
| - | not identified | ++ | subdominant |
| ? | Identification uncertain | +++ | dominant |
| tr | trace | ++++ | most dominant |
| + | accessory | | |

Table 15 - Summary of Mineralogy by XRD on Weak Rock to Soil Grades of Weathered Granite

| Description | | Sample No | Feldspars $P_f$ | Feldspars $K_f$ | Quartz | Micas | Kaolin Minerals | Chlorite | Iron Oxides | Gibbsite | Approx. H/K ratio (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Highly | (Weak rock) | GHG4 | SD | CD | CD | Tr | - | Tr | - | - | n.d. |
| Decomposed | (V. weak rock) | GHG5 | - | CD | CD | Tr | A | - | - | - | n.d. |
| Completely | (Very dense) | GHG6 | - | CD | CD | Tr | A | - | - | - | n.d. |
| Decomposed | (Dense) | 404.05 | - | A | D | A | A-SD(H) | - | Tr(F,G)* | - | 100 |
| | (Dense) | SH8 | - | A | SD | A | D(HK) | - | Tr(G) | - | 2:1 |
| | (Dense) | SH6 | - | A | D | A | A(HK) | - | A(G) | - | 3:1 |
| | (Loose, slightly altered) | 404.06 | - | Tr | D | A | SD(HK) | Tr | Tr(G, F)* | - | 3:1 |
| | (Dense, altered) | SH5 | - | A | D | A | SD(HK) | - | Tr(G) | - | 2:1 |
| | (Loose, disintegrated) | 404.07 | - | Tr | CD | A | CD(H-K) | Tr | Tr(G)* | - | 1:1 |
| Transition | (Small fabric loss) | SH7 | - | Tr-A | D | A | SD(HK) | - | Tr(G) | - | 2:1 |
| Soil | (Large fabric loss) | SH3 | - | Tr-A | D | A | SD(KH) | | Tr(G) | | 1:3 |
| Residual | | GHG7 | - | Tr | CD | Tr | CD | - | Tr | Tr | n.d. |
| Soil | | 404.08 | - | - | SD | Tr | D(KH) | Tr | Tr-A(G)* | Tr | 1:3 |

Legend: $P_f$-Plagioclase feldspar, $K_f$-Alkali feldspar, (K-Kaolinite, H-Halloysite), first more dominant, F-Ferrihydrite, G-Goethite.
n.d. Not determined.
D-Dominant - Used for component apparently most abundant, regardless of its probable percentage level.
CD-Codominant - Used for two (or more) predominating components, both or all of which are judged to be present in roughly equal proportions.
SD-Subdominant - The next most abundant component(s) with percentage level >20%.
A-Accessory - Component judged to be between 5% and 20%.
Tr-Trace - Component judged to be less than 5%.
- Not detected.
* positively identified by XRD on concentrates and by Infrared by Awoleye (1991).

Table 16 - Mineral Contents (% Weight) of Soil Grades of Weathered Granite Calculated from Chemical Analysis

| Description | Sample No | Mineral Content, % | | | | | |
|---|---|---|---|---|---|---|---|
| | | Alkali Feldspar | Quartz | Kaolinite/ Halloysite | Micas | Goethite | Others[1] |
| Completely Decomposed | H1 | 18.6 | 46.3 | 28.9 | 1.0 | 1.7 | 3.5 |
| | SH8 | 10.2 | 48.3 | 28.5 | 7.0 | 1.9 | 4.5 |
| | SH6 | 7.7 | 49.0 | 32.8 | 4.0 | 2.9 | 3.6 |
| | SH5 | 8.2 | 48.5 | 31.9 | 7.0 | 1.5 | 2.9 |
| Transition Soil | SH7 | 13.4 | 43.8 | 31.7 | 5.0 | 1.4 | 4.7 |
| | SH3 | 3.5 | 52.8 | 35.5 | 3.5 | 1.8 | 2.9 |
| Completely Decomposed (Altered) | KP1 | 1.0 | 44.2 | 45.6 | 1.4 | 3.3[2] | 4.5 |
| | KP2 | 1.0 | 44.6 | 45.4 | 1.5 | 3.1[2] | 4.4 |

Notes :
1. Others are excess LOI after deductions of the measured moisture and minor elements not included in the calculations.
2. May be largely hematite.

Table 17 - Classification of Weathering Grades of Granites in Terms of Petrological Changes in the Rock Material (Sheet 1 of 4)

| Material Weathering Grade | Hand Specimen | Fabric Properties | | Mineralogical Composition[1] | | Relative Strength |
|---|---|---|---|---|---|---|
| | Visual effects | Decomposition of primary minerals | Microfracturing/ pore development/ grain boundaries | Primary Minerals | Secondary Minerals | |
| Fresh | Light grey to pinkish grey. Granular crystalline textures with grain size varying from fine (less than 1 mm) to coarse (over 6 mm); equigranular to inequigranular to megacrystic. | All minerals unaltered, except for minor sericite (hydrous mica) growth in plagioclases and partial chloritization of biotite. | Rock fabric unfractured, except in tectonically affected granites. Occasional short intergranular microcracks. | Q (CD)<br>Pf (CD)<br>Kf (CD)<br>B(A-Tr) | M (?-Tr)<br>C (?-Tr) | Very strong to extremely strong |
| Slightly Decomposed | (i) <u>Slightly Discoloured</u> : Less than 10% staining. Some feldspars (plagioclases) slightly gritty in the stained rim. | <u>Fresh core</u> : Similar to fresh rock.<br><u>Stained rim</u> : Plagioclases slightly decomposed to micaceous minerals. Biotite slightly decomposed. | Rock fabric unfractured.<br><br>Occasional microcracks in feldspars, quartz; simple transgranular tight micro-cracks. Grain boundaries stained but tight. | Q (CD)<br>Pf (CD)<br>Kf (CD)<br>B (Tr) | M (Tr)<br>C (Tr) | Very strong<br><br>Very strong |
| | (ii) <u>Moderately Discoloured</u> : 10% to 50% staining.<br>(iii) <u>Highly Discoloured</u> : More than 50% staining. Colour banding may be present. Plagioclases partially gritty.<br>A series of parallel microcracks may be present in the vicinity of discontinuity surfaces in the stained rim. | <u>Fresher core</u> : Plagioclases slightly decomposed.<br><u>Stained rim</u> : Plagioclases slightly to moderately decomposed to micaceous minerals and trace kaolin. | Few tight intragranular and short transgranular microcracks. Some etch-pits and etch-trench type solution in feldspars. Stained transgranular microcracks. Some grain boundaries stained indicating solution and microfracturing. | Q (CD)<br>Kf (CD)<br>Pf (CD)<br>B (Tr) | M (Tr-A)<br>Int[3] (?)<br>H/K (?-Tr)<br>C (Tr) | to<br><br>Strong |

Table 17 - Classification of Weathering Grades of Granites in Terms of Petrological Changes in the Rock Material (Sheet 2 of 4)

| Material Weathering Grade | Hand Specimen | Fabric Properties | | Mineralogical Composition[1] | | Relative Strength |
|---|---|---|---|---|---|---|
| | Visual effects | Decomposition of primary minerals | Microfracturing/ pore development/ grain boundaries | Primary Minerals | Secondary Minerals | |
| Moderately Decomposed | Completely discoloured yellowish brown (dark brown along discontinuities). Plagioclases gritty, alkali feldspars microfractured. Tight microfractures throughout.<br><br>(Cannot be broken by hand, easily broken by hammer) | Plagioclases slightly to highly decomposed to kaolin minerals. Slight decomposition and solution in alkali feldspars. Biotite slightly decomposed. | Etch-pit and etch-trench type pore development in plagioclases (barely visible under microscope). Branched tight to slightly open transgranular microcracks. Some grain boundaries microfractured. | Q (CD)<br>Kf (CD)<br>Pf (A)<br>B (Tr) | M (Tr-A)<br>H (Tr)<br>$K^{2,3}$(Tr)<br>F (Tr)<br>G (Tr)<br>$H^{4}$ (?) | Strong to<br><br>moderately strong |
| Highly Decomposed | Yellowish grey to yellowish brown. Plagioclases gritty to powdery in weak rock range to powdery to soft in very weak rock. Alkali feldspars hard to gritty. Biotite greenish black to dull grey, soft. Highly microfractured; horizontal partings may be present.<br><br>(less weathered specimens can be broken by hand, more weathered specimens broken into a mixture of friable rock fragments and individual mineral grains). | Plagioclases highly to completely decomposed to halloysite, with some kaolinite. Varying degrees of pore development in Alkali feldspars. Biotite partially to completely changed into clay minerals, hydrous mica and iron oxides; slight expansion of lattice. | Highly fractured by complex-branched slightly open transgranular, intra- and intergranular microcracks. Numerous solution pores and channels in alkali feldspars. | Q (D)<br>Kf (SD-A)<br>Pf (Tr)<br>B (Tr-?) | H (Tr-A)<br>M (Tr-A)<br>$K^{2,3}$ (Tr)<br>C (Tr)<br>F (Tr)<br>G (Tr)<br>$H^{4}$ (?) | Moderately weak<br><br>to<br><br>Very weak |

Table 17 - Classification of Weathering Grades of Granites in Terms of Petrological Changes in the Rock Material (Sheet 3 of 4)

| Material Weathering Grade | Hand Specimen | Fabric Properties | | Mineralogical Composition[1] | | Relative Strength |
|---|---|---|---|---|---|---|
| | Visual effects | Decomposition of primary minerals | Microfracturing/ pore development/ grain boundaries | Primary Minerals | Secondary Minerals | |
| Completely Decomposed | Yellowish grey to yellowish brown but may be mottled (in groundwater fluctuation zone), or pinkish or greyish colour if altered or leached.<br><br>i) Very dense a) Decomposed<br>ii) Dense b) Disintegrated<br>iii) Loose c) Altered<br><br>In (normally) decomposed type plagioclases decomposed to powdery to soft grains, alkali feldspars gritty. Granitic fabric preserved but highly fractured.<br><br>(Can be crumbled into individual soil grains by finger pressure, slakes in water). | Plagioclases completely decomposed to halloysite with some kaolinite. In near-surface specimens and in granite affected by alteration kaolinite may become dominant. Alkali feldspars porous to honeycombed with little clay mineral formation. Minor solution of quartz. Biotite completely replaced by micaceous and kaolin minerals and may show exfoliation by expansion. | Fabric highly microfractured by open complex-branched microcracks. Most grain boundaries open but some intact. Clay mineral and iron-oxide bridges may be present between grains. Numerous pores and solution channels in alkali feldspars. Different clay minerals and microfabrics can develop in both feldspar types and biotite, even in the same specimen, depending on intensity of weathering, alteration and leaching conditions. | Q (D)<br>Kf (A)<br>Pf (Tr-Nil) | H (A-SD)<br>K[2,5] (Tr-a)<br>M/I (Tr)<br>C (Tr-?)<br>G (Tr)<br>H[4] (?)<br>F (?) | Extremely weak rock or very dense soil<br><br>to<br><br>loose soil |
| Transition Soil | Mottled yellowish grey and reddish brown with gradual loss (collapse) of granitic fabric upwards in the profile. Relict joints not present in soil mass.<br><br>(Can be crumbled into individual soil grains by finger pressure, easily slakes in water except when locally weakly cemented). | Feldspars absent except in areas still retaining fabric. Alkali feldspars highly to completely decomposed to kaolinite. Goethite occurs as aggregations/coatings. Kaolinite becomes dominant up the sequence. Minor gibbsite may be present. | Soil composed of areas of microfractured and porous, decomposed granitic fabric and collapsed areas of silt to sand size quartz in a dense to porous clayey fabric. Quartz extremely microfractured and broken into smaller fragments. | Q (D)<br>Kf (Tr-Nil) | K (SD-CD)<br>H (SD)<br>M/I (Tr)<br>G (Tr-A)<br>Gi[6] (?-Tr)<br>C (?) | Loose to Dense |

Table 17 - Classification of Weathering Grades of Granites in Terms of Petrological Changes in the Rock Material (Sheet 4 of 4)

| Material Weathering Grade | Hand Specimen | Fabric Properties | | Mineralogical Composition[1] | | Relative Strength |
|---|---|---|---|---|---|---|
| | Visual effects | Decomposition of primary minerals | Microfracturing/ pore development/ grain boundaries | Primary Minerals | Secondary Minerals | |
| Residual Soil | Light yellowish grey (when leached) to reddish brown. No granitic fabric. All primary minerals except quartz transformed into clay minerals.<br><br>Irregular network of desiccation cracks and large pores may be present. | Feldspars absent except for occasional fragments. Kaolinite is the dominant clay mineral. A small amount of gibbsite may form in well-drained areas. | Granitic fabric completely destroyed. Large pores and secondary cracks in generally dense clayey fabric which may contain up to 50% fine sand to silt size quartz grains. Aggregations of goethite and weak cementation by clay and iron-oxide bridges may be present. | Q (CD)<br>Kf (?) | K (CD)<br>H (A)<br>Gi[6] (Tr)<br>M/I (Tr)<br>G (Tr-A)<br>C (?)<br>H[4] (?) | Dense clayey silty sand to sandy clayey silt (may be weakly cemented) |

Notes : Q-Quartz, Pf-Plagioclase, Kf-Alkali feldspar, B-Biotite, M-Muscovite/hydrous mica, I-Illite, C-Chlorite, K-Kaolinite, H-Halloysite, G-Goethite, Int-Amorphous alumina silicate or disordered kaolinite, Gi-Gibbsite, F-Ferrihydrite, H-Hematite.

1. See Table 8 for dominance scales for mineralogical composition (excluding pore content).
2. Kaolinite may be formed directly from feldspar in granite affected by hydrothermal alteration.
3. Poorly crystalline kaolinite may form through an amorphous alumina-silicate gel in early stages of weathering.
4. Hematite may be present if original rock contains magnetite.
5. Kaolinite may be dominant if rock is intensely altered.
6. Gibbsite is formed in well-drained sites, but not abundant in Hong Kong.

Small amount of primary muscovite and hornblende may be present in some granites.
Smectite, although not encountered in any analysis of Hong Kong granites to date, may form in poorly drained, stagnant conditions (e.g. valley bottoms).

Table 18 - Classification of Granitic Residual and Saprolitic Soils in Hong Kong

| Engineering Mass Weathering Grade or Zone (based on BSI, 1981 and this document) | | Residual Soil Group (Wesley & Irfan, 1994, See Table 5) | Macro (mass) & Microstructure | Dominant Minerals[1] in Soil Material |
|---|---|---|---|---|
| Top Soil | | | | |
| Residual Soil | | Group A(c) (thin layers or lenses of Group C(c) may form near ground surface particularly in poorly drained areas).<br>(Mature residual soils of Group C(c) are not generally present in Hong Kong). | No relict mass structure; no original bonding but weak secondary[2] bonding except in thin C(c) soil; original fabric completely destroyed by collapse/soil creep. | Kaolinite with quartz (silt to sand size), some goethite; minor gibbsite in well drained areas[3] (Local concentration of goethite/hematite in Group C(c)). |
| Transitional Soil | | Transitional between Group A(c) and Group A(b), possible thin lenses/layers of C(c) in groundwater fluctuation zones. | No relict mass structure; partial (decomposed/disintegrated) granitic fabric decreasing upwards in weathering profile; very weak secondary[2] bonding. | Quartz with kaolinite, some halloysite, minor goethite and illite. |
| Saprolite | Completely Weathered | Group A(b)<br><br>to<br><br>Group A(a) | Relict joints and other mass features preserved; original granitic fabric preserved; dominantly composed of loose to medium dense[7] material with very weak relict[5] bonding, and occasional less weathered rock (corestones)<br><br>Dominantly composed of dense[7] to very dense material with weak relict bonding, and up to 10% less weathered rock (corestones) | Quartz with kaolinite and halloysite[6], some partial decomposed K-feldspars, minor goethite and illite.<br><br>Quartz with halloysite and some kaolinite[6] and porous K-feldspar, minor illite. |
| Saprolite | Highly Weathered | Group A(a)<br><br>to<br><br>Not applicable (should be described as partially weathered rock) | Up to 30% partially weathered rock fragments or continuum in loose to very dense soil material<br><br>30 to 50% partially weathered rock in dense to very dense (completely decomposed/disintegrated) soil material or composed of wholly very weak to weak rock (highly decomposed/ disintegrated). | Quartz and K-feldspars with some halloysite, minor unaltered plagioclase, kaolinite, muscovite. |

Notes :
1. Excluding less weathered corestones in soil. See Table 17 for detailed mineralogy.
2. The term 'secondary bonding' is used for those arising from weathering and cementation (e.g. electrochemical bonds between clay minerals)
3. Minor smectite and other swelling minerals may be present in poorly drained areas.
4. Quartz content may be significantly reduced if hydrothermally altered.
5. Original bonding between unweathered grains.
6. Kaolinite may be more dominant if hydrothermally altered.
7. See Table 23 for density terms.

Table 19 - Selected Chemical Indices Used for the Characterization of the Degree of Weathering in Igneous Rocks

| Index | Formula | Reference |
|---|---|---|
| Weathering Potential Index | $WPI = Mole \dfrac{100\,(K_2O + Na_2O + CaO + MgO - H_2O^+)}{SiO_2 + Al_2O_3 + Fe_2O_3 + TiO_2 + CaO + MgO + Na_2O + K_2O}$ | Reiche, 1943<br>Ruxton, 1986 |
| Weathering Product Index | $PI = Mole \left[\dfrac{100\,SiO_2}{SiO_2 + TiO_2 + Fe_2O_3 + Al_2O_3}\right]$ | Reiche, 1943<br>Ruxton, 1968 |
| Silica to Alumina Ratio | $SA\ ratio = Mole \left[\dfrac{SiO_2}{Al_2O_3}\right]$ | Ruxton, 1968 |
| Alumina to Potassium-Sodium Oxide Ratio | $AKN\ ratio = \dfrac{Al_2O_3}{K_2O + Na_2O}$ | |
| Alumina to Calcium-Sodium Oxide Ratio | $ACN\ ratio = \dfrac{Al_2O_3}{Al_2O_3 + CaO + Na_2O}$ | Harnois & Moore, 1988 |
| Lixiviation Index | $\beta = \dfrac{\left[\dfrac{K_2O + Na_2O}{Al_2O_3}\right]_{weathered}}{\left[\dfrac{K_2O + Na_2O}{Al_2O_3}\right]_{fresh} + \dfrac{CaO}{MgO}}$ | Rocha filho et al, 1985 |
| Mobiles Index | $I_{mob} = Mole \left[\dfrac{(K_2O + Na_2O + CaO)_{fresh} - (K_2O + Na_2O + CaO)_{weathered}}{(K_2O + Na_2O + CaO)_{fresh}}\right]$ | Irfan, 1994 (this document) |
| Loss on Ignition | $LOI = H_2O^+$ content (in weight) of specimen heated beyond 105°C. | Suoeka et al, 1985 |

Table 20 - Chemical Weathering Indices, Weathered Granite, Shouson Hill

| Sample No. | WPI | PI | SA ratio | AKN ratio | ACN ratio | β | Imob | LOI % |
|---|---|---|---|---|---|---|---|---|
| HG2 (SHS12) | 6.57 | 90.66 | 10.16 | 1.49 | 0.77 | 0.01 | 0.00 | 0.38 |
| HG3 (SHS10) | 4.39 | 90.87 | 10.47 | 1.55 | 0.79 | 0.00 | 0.11 | 0.76 |
| HG4S (SHS8) | 0.08 | 89.90 | 9.68 | 1.75 | 0.87 | 0.12 | 0.23 | 1.67 |
| HG4 (SHS9) | -8.45 | 89.19 | 8.75 | 2.48 | 1.00 | 0.60 | 0.48 | 3.37 |
| HG4W (SHS6) | -9.56 | 89.19 | 8.90 | 3.13 | 1.00 | 0.19 | 0.59 | 3.41 |
| HG5D2 (SHS5) | -9.47 | 90.89 | 10.91 | 2.87 | 1.00 | 0.52 | 0.62 | 3.36 |
| HG5D1 (SHS5) | -20.29 | 81.36 | 4.64 | 3.80 | 0.99 | 0.39 | 0.46 | 6.06 |
| HG5L (SHS7) | -21.64 | 87.48 | 7.64 | 12.68 | 1.00 | 0.01 | 0.88 | 5.81 |
| HG6 (SHS1) | -25.59 | 86.76 | 7.16 | 31.40 | 1.00 | 0.05 | 0.95 | 6.58 |

Table 21 - Chemical Weathering Indices, Soil Grades of Weathered Granite

| Description | Sample No. | WPI | PI | SA ratio | AKN ratio | ACN ratio | β | Imob | LOI % |
|---|---|---|---|---|---|---|---|---|---|
| V. weak rock | HG4 | -8.45 | 89.19 | 8.75 | 2.48 | 1.00 | 0.60 | 0.48 | 3.37 |
| V. weak rock | HG4W | -9.56 | 89.19 | 8.90 | 3.13 | 1.00 | 0.19 | 0.59 | 3.41 |
| V. dense (decomposed) | HG5D2 | -9.47 | 90.89 | 10.91 | 2.87 | 1.00 | 0.52 | 0.62 | 3.36 |
| Dense (altered) | HG5D1 | -20.29 | 81.36 | 4.64 | 3.80 | 0.99 | 0.39 | 0.46 | 6.06 |
| Loose (decomposed) | GH5L | -21.64 | 87.48 | 7.64 | 12.68 | 1.00 | 0.00 | 0.88 | 5.81 |
| Loose (decomposed) | SH8 | -26.81 | 87.60 | 7.66 | 5.79 | 0.99 | 0.18 | 0.75 | 7.30 |
| Loose (decomposed) | SH6 | -27.87 | 87.17 | 7.59 | 8.20 | 0.99 | 0.11 | 0.81 | 7.40 |
| Loose (altered) | SH5 | -23.06 | 87.20 | 7.25 | 7.27 | 0.99 | 0.15 | 0.79 | 6.30 |
| Small fabric loss | SH7 | -29.74 | 86.80 | 6.98 | 5.61 | 0.99 | 0.15 | 0.72 | 8.00 |
| Large fabric loss | SH3 | -25.35 | 87.83 | 7.76 | 15.09 | 1.00 | 0.07 | 0.90 | 6.65 |
| Residual Soil | HG6 | -25.56 | 86.68 | 7.16 | 31.40 | 1.00 | 0.00 | 0.95 | 6.58 |
| Dense (decomposed) | H1 | -20.01 | 88.25 | 8.06 | 4.54 | 0.99 | 0.25 | 0.70 | 5.75 |
| (altered) | KP2 | -40.57 | 84.48 | 6.09 | 51.94 | 0.99 | 0.01 | 0.95 | 9.85 |
| (altered) | KP1 | -39.40 | 84.33 | 6.05 | 51.94 | 0.99 | 0.01 | 0.96 | 9.50 |

Table 22 - Variation in Physical Properties of Weathered Granite, Shouson Hill

| Sample No. | Dry Bulk Density g/cm³ | | Specific Gravity | | Relative Voids Volume | Porosity % |
|---|---|---|---|---|---|---|
| HG2 (GHG1) | - | (2.61) | - | (2.64)[2] | - | (1.08) |
| HG2 (GHG2) | 2.53 | (2.58) | 2.58 | 2.58 | 2.07 | (1.91) |
| HG3 (GHG3) | 2.51 | (2.55) | 2.57 | 2.57 | 3.43 | (2.95) |
| HG3 (GHG4) | - | (2.52) | - | - | - | (3.89) |
| HG4S | 2.28 | - | 2.57 | 2.57 | 16.78 | |
| HG4 | 1.79 | - | 2.51 | 2.51 | 53.07 | |
| HG5D-2 | 1.85 | - | 2.52 | 2.52 | 51.73 | |
| HG4W | 1.77 | (1.78) | 2.48 | 2.48 | 54.17 | |
| HG5D1 | 1.56 | - | 2.21 | 2.21 | 63.50 | |
| HG5L | 1.46 | - | 2.15 | 2.15 | 72.63 | |
| SH8 | - | (1.21)[1] | - | (2.62)[1] | - | |
| SH6 | - | (1.24)[1] | - | (2.62)[1] | - | |
| SH5 | - | (1.29)[1] | - | (2.63)[1] | - | |
| SH7 | - | (1.22)[1] | - | (2.62)[1] | - | |
| SH3 | - | (1.26)[1] | - | (2.63)1 | - | |
| HG6 | 1.66 | - | 2.42 | - | 63.20 | |

Notes : ( ) Determined on duplicate block samples/specimens by the standard methods. Others are from Hencher (1990) by Mercury Intrusion Porosimetry technique; average of three results on specimens taken from the tops of block samples.

1. Determined on small direct shear specimens (Irfan, 1988) by the standard methods (BSI, 1975).
2. Average for fresh to slightly decomposed medium-grained granites (Irfan, 1994a)

Table 23 - Classification of Weathering Grades in Hong Kong Granites in Terms of Dry Density

| Weathering Grade | (Subgrade) or Strength | | Dry Bulk Density $kg/m^3 \times 10^3$ |
|---|---|---|---|
| Fresh | | | 2.58 to 2.63 |
| Slightly Decomposed | (Slightly discoloured)<br>(Moderately discoloured)<br>(Highly discoloured) | | 2.55 to 2.60 |
| Moderately Decomposed | M.weak to M.strong | | 2.30 to 2.58 |
| Highly Decomposed | M.weak<br>V.weak to weak | | 2.00 to 2.40<br>1.70 to 2.00 |
| Completely Decomposed | (Decomposed/<br>Altered/<br>Disintegrated) | Very Dense<br>Dense<br>Loose | 1.60 to 1.80<br>1.40 to 1.60<br>1.20 to 1.40 |
| Transitional Soil | | | 1.25 to 1.60 |
| Residual Soil | | | 1.25 to 1.60 |

Table 24 - Comparison of Material Classification of Weathered Granites in Terms of Insitu Schmidt Hammer Values

| Weathering Grade | Schmidt Hammer Value (N-type) | | | |
|---|---|---|---|---|
| | Coarse-grained granite, Hong Kong (Data from Irfan & Cipullo, 1989) | Granites Hong Kong (Hencher & Martin, 1982) | Granodiorite Tai Po (Irfan & Powell, 1985) | Granites U.K. (Dearman & Irfan, 1978) |
| Fresh | (57-60)[1] | nr | 59-68 | 58-66 |
| Slightly Decomposed | >55 | >45 | 45-68 | 53-58 |
| Moderately Decomposed | 30-58 | 25-45 | 25-50 | 45-58 |
| Highly Decomposed | 14[2]-32 | 0-25 | 15-30 | 20-45 |
| Completely Decomposed: V. Dense<br>Dense<br>Loose | 12[2]-18<br><10[3]-14<br>0-<10[3] | 0 | 0-18 | <20 |
| Transition & Residual Soil | 0 | 0 | 0 | 0 |

Notes :
1. From Irfan (1994a) on block samples of fine to coarse-grained granites.
2. Lower values are possible if rock is hydrothermally altered.
3. Hammer not sensitive to values below 10.

nr Not reported.

Table 25 - Micropetrographic Indices for Weathered Granite, Shouson Hill

| Description | Sample No. | Altered Minerals % | Sound Minerals % | Microcracks and Voids % | Micropetrographic Index Ip | Decomposition Index $Xd_{mod}$ |
|---|---|---|---|---|---|---|
| Fresh | - | 2.3 | 97.1 | 0.6 | 33.48 | n.d |
| | GHG1 | 3.9 | 95.6 | 0.5 | 21.73 | n.d |
| | 404.01 | 3.6 | 96.0 | 0.4 | 24.00 | n.d |
| Slightly Decomposed | GHG2 | 5.9 | 93.4 | 0.5 | 14.59 | n.d |
| | 404.02f | 7.0 | 92.0 | 1.1 | 11.36 | n.d |
| | 404.02s | 9.7 | 87.2 | 3.1 | 6.81 | n.d |
| Moderately Decomposed | GHG3 | 9.3 | 88.2 | 2.4 | 7.54 | n.d |
| | 404.03 | 7.0 | 90.0 | 2.8 | 9.18 | n.d |
| | GHG4 | 12.6 | 84.4 | 3.0 | 5.41 | n.d |
| Highly Decomposed | HG4S | n.d | n.d | n.d | n.d | n.d |
| | GHG5 | 38.0 | 46.4 | 15.6 | 0.87 | n.d |
| Completely Decomposed | GHG6 | 29.5 | 54.7 | 15.6 | 1.21 | n.d |
| | 404.05 | 31.9 | 49.4 | 18.5 | 0.98 | n.d |
| | SH8 | 42.4 | 34.6 | 22.9 | 0.53 | 0.62 |
| | SH6 | 44.4 | 31.7 | 23.7 | 0.47 | 0.73 |
| | 404.06 | 38.2 | 37.7 | 24.0 | 0.61 | n.d |
| | SH5 | 33.1 | 43.1 | 23.6 | 0.76 | 0.94 |
| | SH5a | 48.8 | 28.8 | 22.3 | 0.41 | 0.97 |
| | 404.07 | 33.7 | 28.1 | 38.0 | 0.39 | n.d |
| Transition Soil | SH7 | 50.1 | 24.9 | 24.8 | 0.33 | 0.89 |
| | SH3 | 58.6 | 27.9 | 13.5 | 0.39 | 0.92 |
| Residual Soil | 404.08 | 59.6 | 26.9 | 13.2 | 0.37 | n.d |
| | GHG7 | 56.3 | 29.0 | 14.5 | 0.41 | n.d |

Notes : Modal analysis is carried out on one thin section per specimen, except in SH series (3-4 thin sections per specimen), f - fresh core, s - stained rim, 1a -altered portion

Table 26 - Particle Size Distribution Shouson Hill

| Description | | Sample No. | Particle Size Distribution | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Standard Methods | | | | | Finger-Crushing | | | | |
| | | | G | S | M | C | M&C | G | S | M | C | M&C |
| Highly | (V.weak) | HG4[1] | 40 | 52 | 7 | 1 | 8 | - | - | - | - | - |
| Decomposed | (V.weak) | HS4 | 55 | 41 | 3 | 1 | 4 | 50 | 43 | 5 | 2 | 7 |
| Completely | | HG5D | 38 | 49 | 11 | 2 | 13 | - | - | - | - | - |
| Decomposed | | 404.05 | 47 | 47 | n.d | n.d | 6 | - | - | - | - | - |
| | | SH8 | 38 | 47 | 12 | 3 | 15 | 38 | 44 | 13 | 5 | 18 |
| | | SH6 | 42 | 40 | 14 | 4 | 18 | 40 | 42 | 14 | 4 | 18 |
| | | 404.06 | 38 | 51 | n.d | n.d | 11 | - | - | - | - | - |
| | (Disintegrated) | 404.07 | 48 | 34 | 9 | 9 | 18 | - | - | - | - | - |
| | | SH5w | 36 | 38 | 20 | 6 | 26 | 26 | 38 | 30 | 6 | 36 |
| | (Altered) | SH5a | 34 | 35 | 25 | 6 | 31 | 26 | 31 | 34 | 9 | 43 |
| | (Kaolinized) | HS3 | 6 | 30 | 56 | 8 | 64 | 5 | 26 | 60 | 9 | 69 |
| Transition | | SH7 | 40 | 45 | 11 | 4 | 15 | 24 | 38 | 26 | 12 | 38 |
| Soil | | SH3 | 31 | 42 | 18 | 9 | 27 | 31 | 39 | 20 | 10 | 30 |
| Residual | | HG6[1] | 27 | 30 | 36 | 7 | 43 | - | - | - | - | - |
| Soil | | 404.08 | 53 | 16 | 13 | 18 | 31 | - | - | - | - | - |

Note : 1. Psd analysis in accordance with BS 1377:1975, others by PWCL method (modified BS1377, using oven drying)

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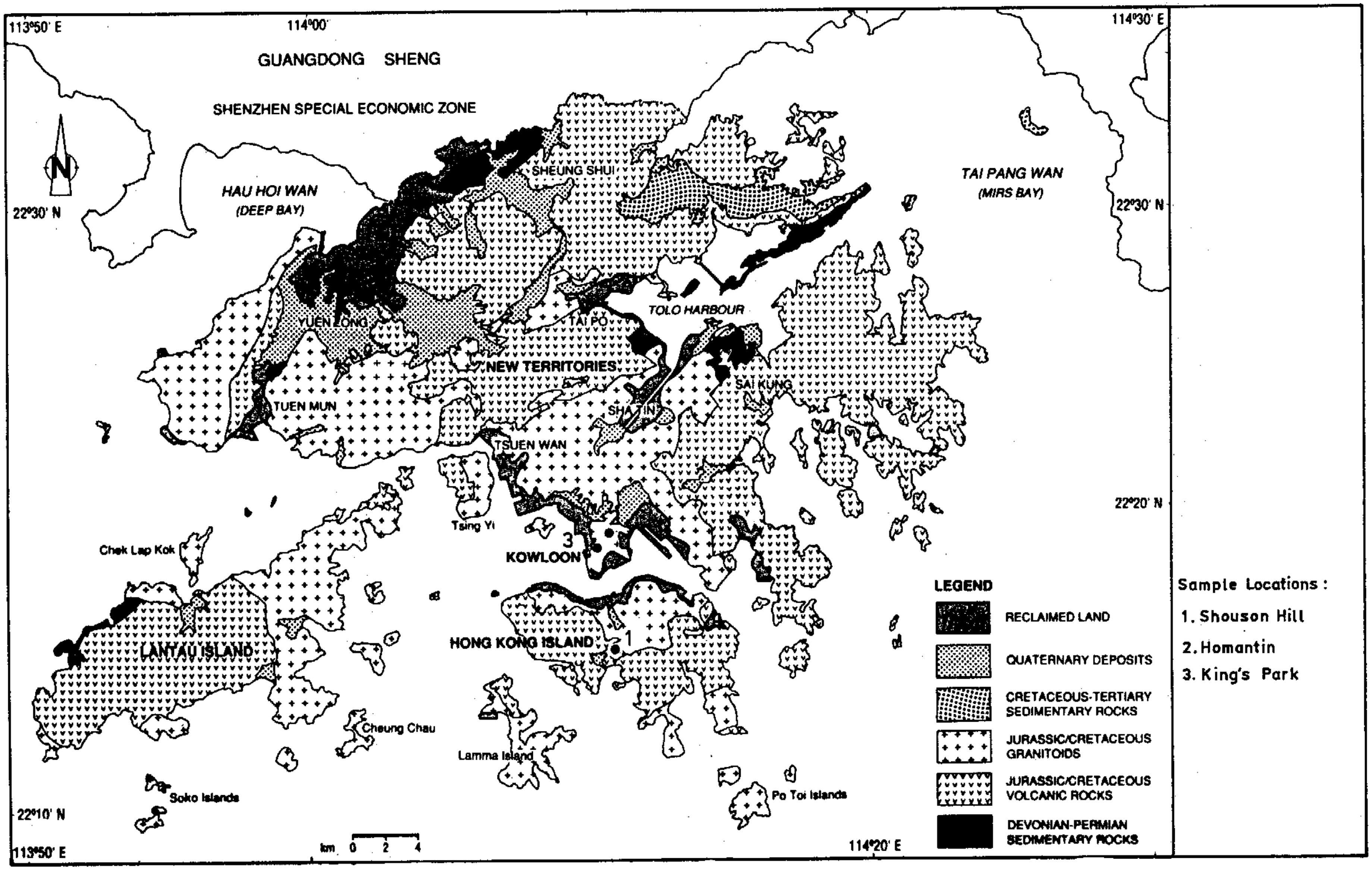
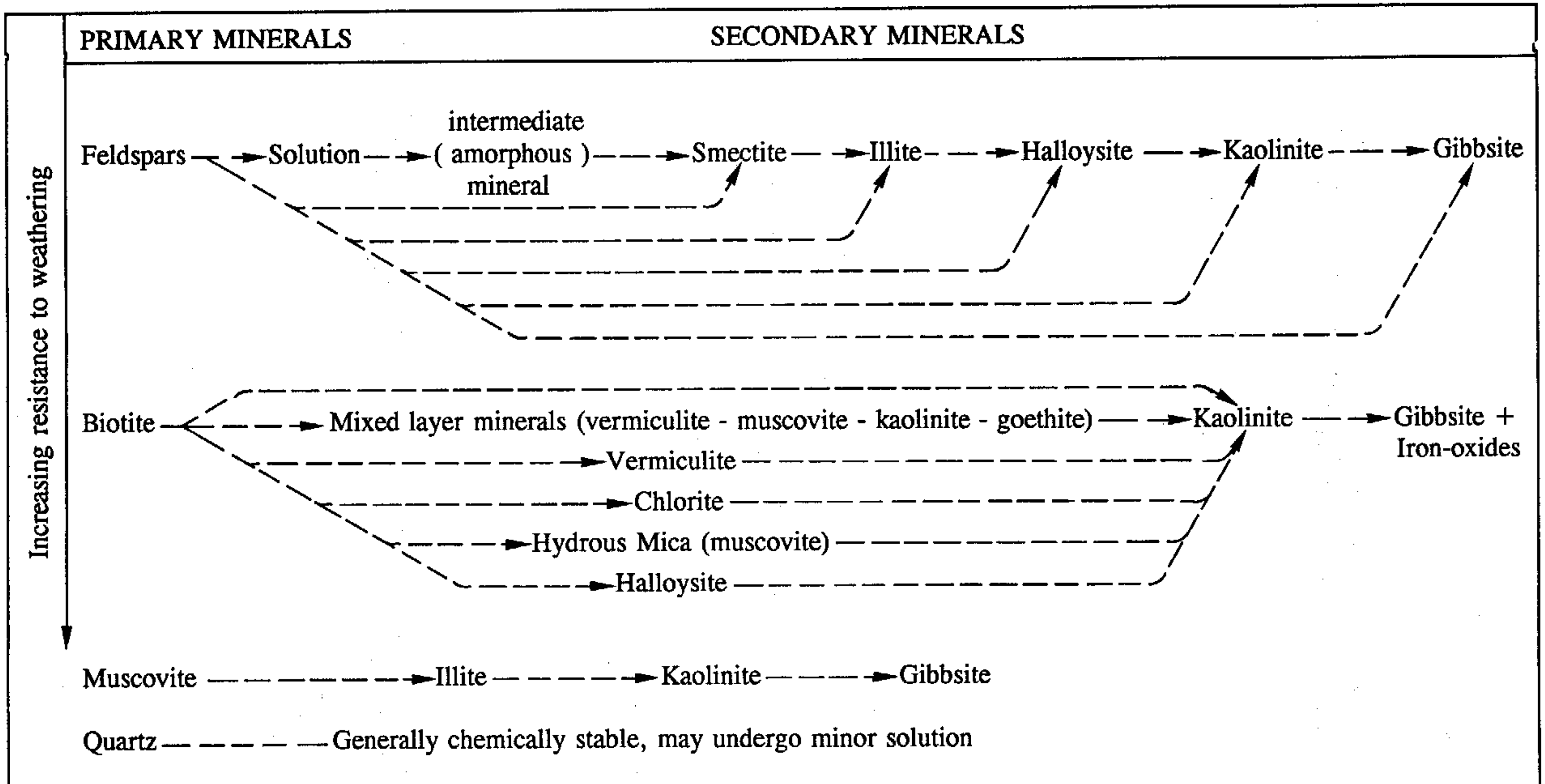



Figure 1 - Geological Map of Hong Kong Showing Locations of Sampling Stations




Notes :
(1) Mineral transformations are based on Wilson (1975), Eswaran & Bin (1978), Gilkes & Suddhiprakaran (1979) and the references given in their papers.
(2) Types of secondary mineral formed depend on the type and concentration of ions present, pH of groundwater, leaching, topographical conditions, etc. Poorly drained conditions favour formation of smectite minerals. Gibbsite may form directly in highly leached conditions and long periods of stable weathering.

Figure 2 - Behaviour of Major Minerals in Acid Igneous Rocks Under Weathering Conditions Dominated by Chemical Weathering

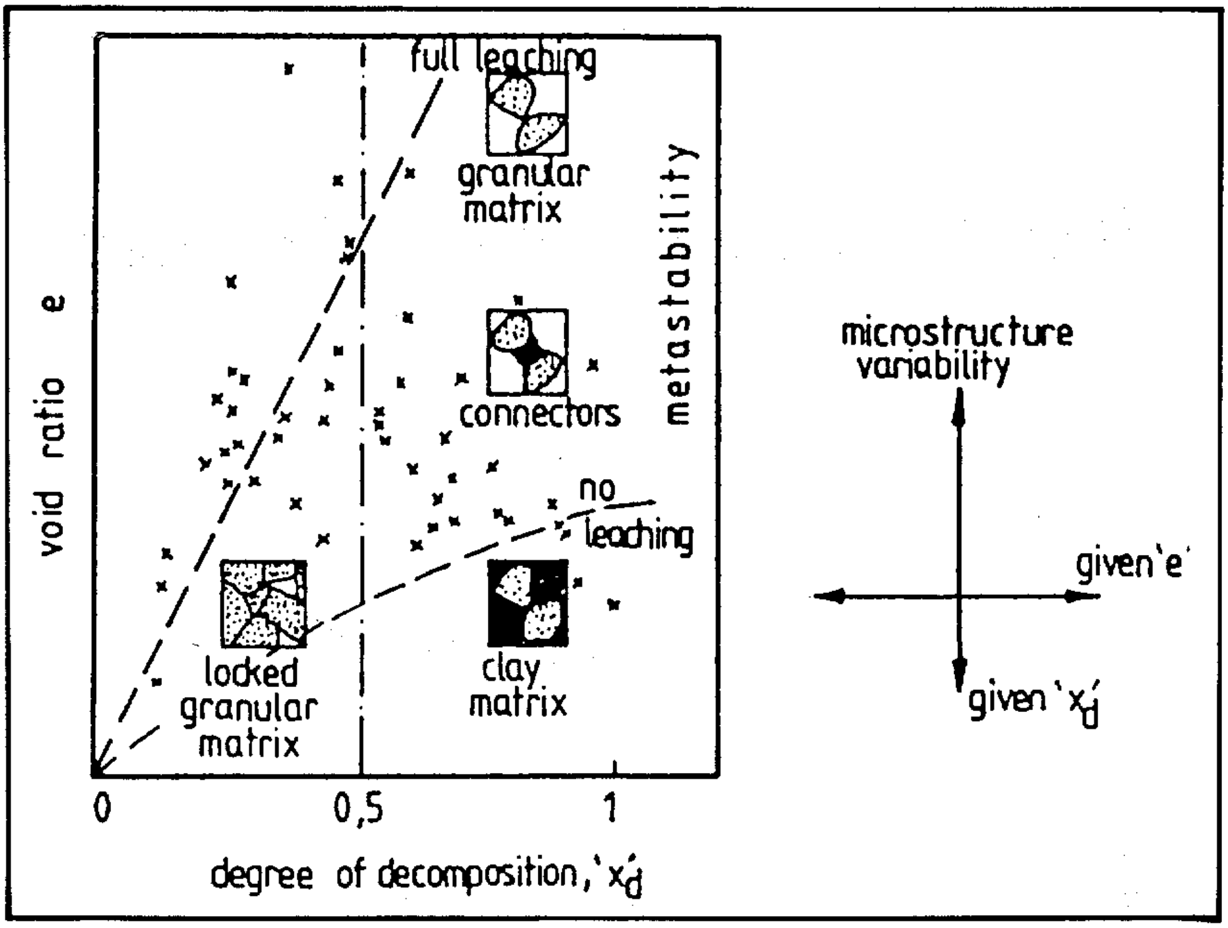



Figure 3 - Microfabric Characterization Scheme Proposed by Collins (1985a)

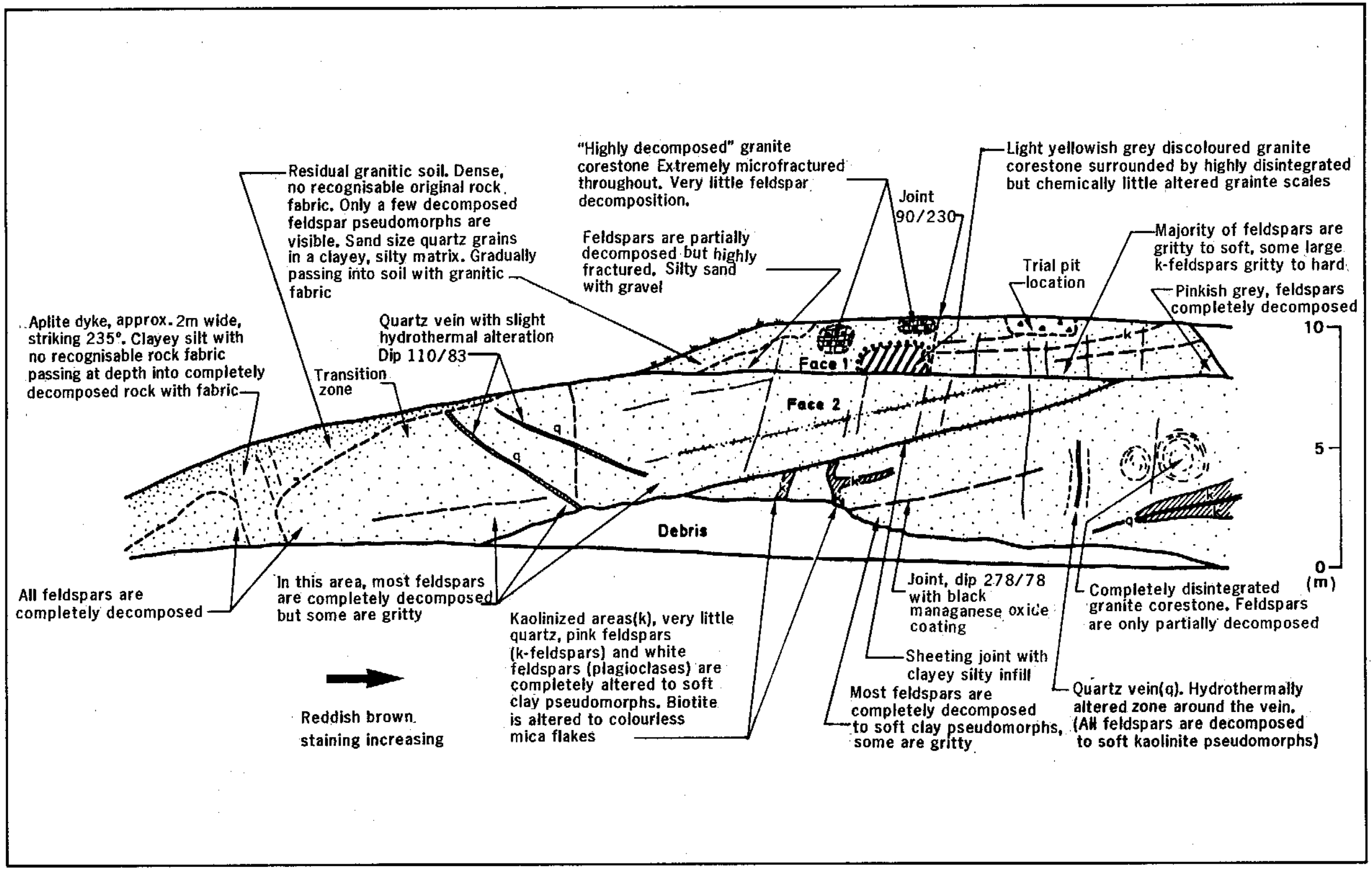



Figure 4 - Variability of Weathering Characteristics of Granitic Saprolite at Shouson Hill (Irfan,1988)

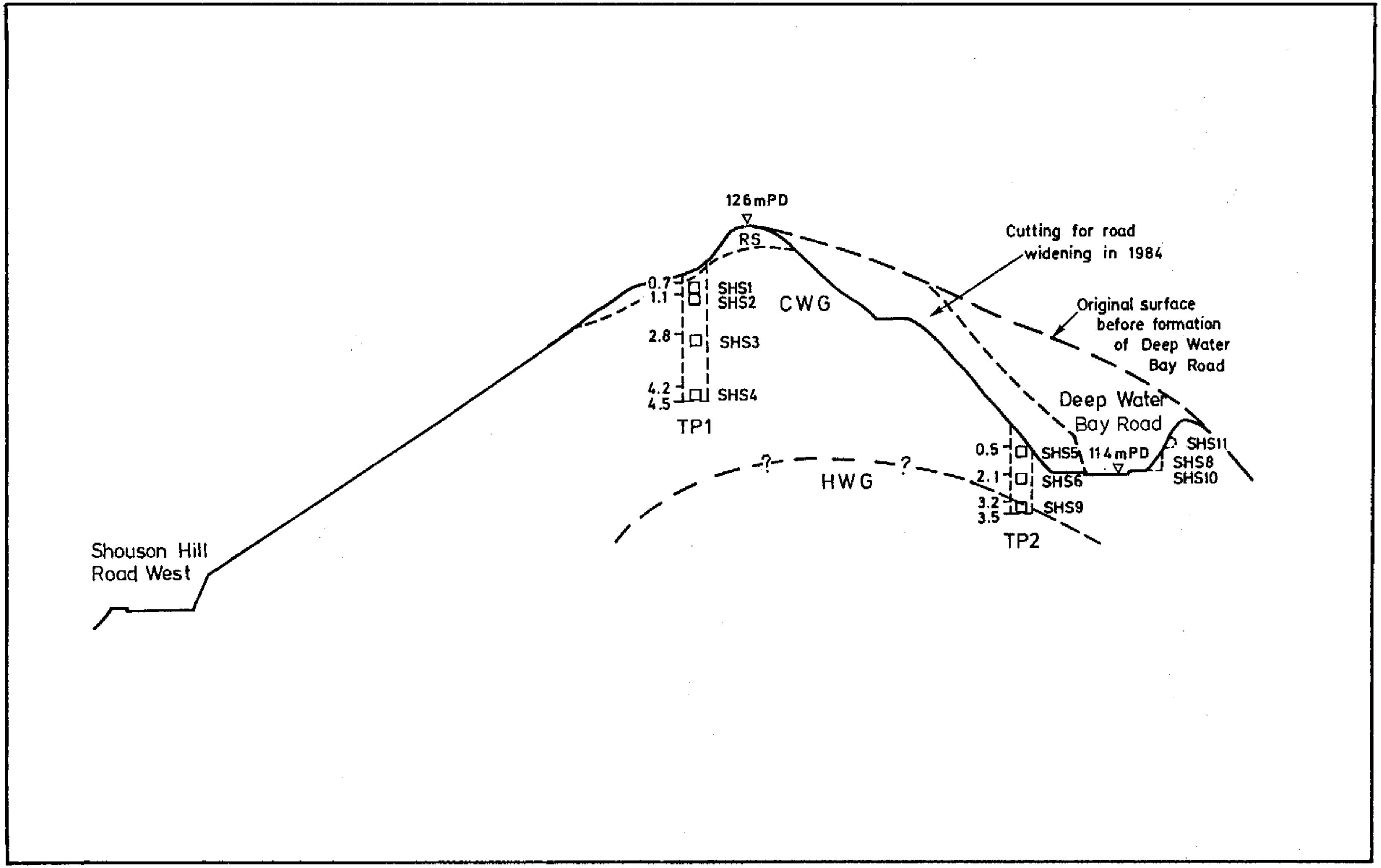
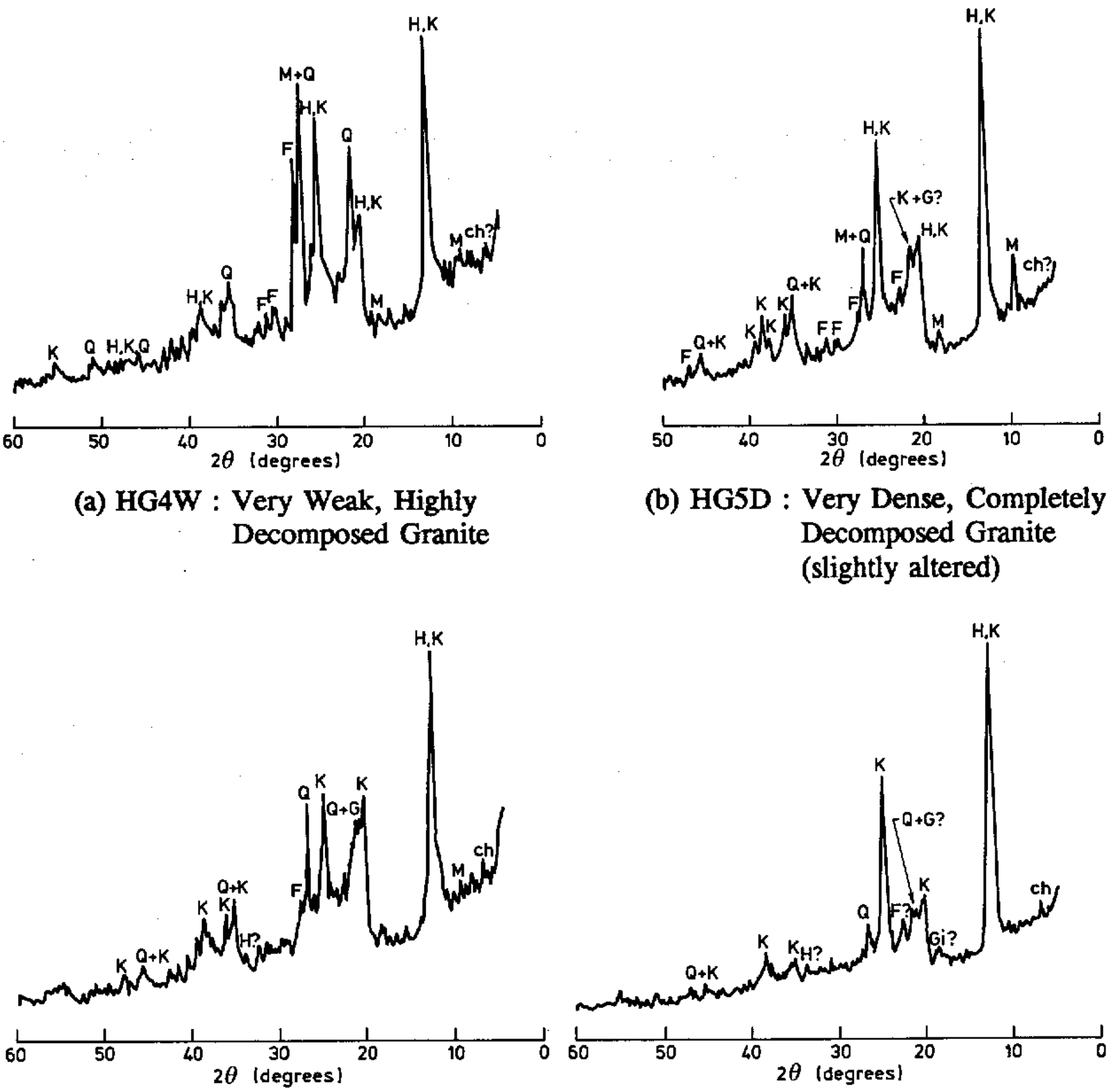



Figure 5 - Sketch Cross-section Showing Locations of Some Samples Used for the Study, Shouson Hill




(a) HG4W : Very Weak, Highly Decomposed Granite

(b) HG5D : Very Dense, Completely Decomposed Granite (slightly altered)

(c) HG5L : Loose, Completely Decomposed Granite

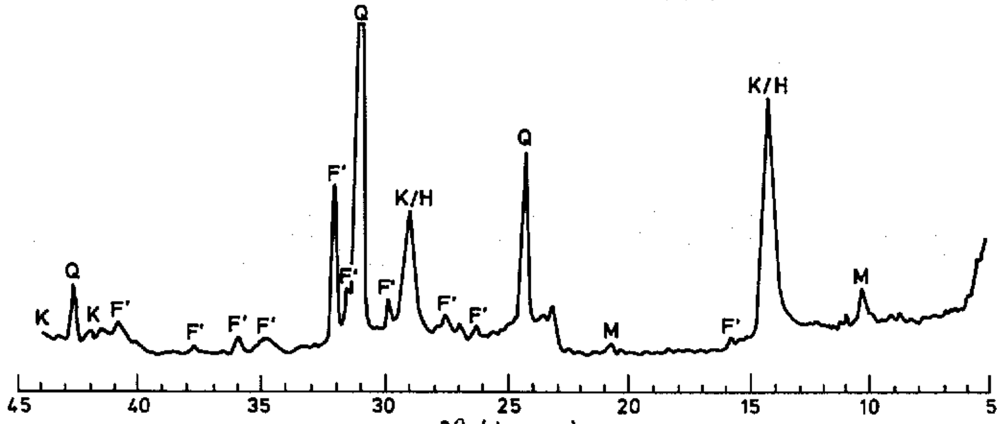
(d) HG6 : Residual Soil of Granite

Legend :

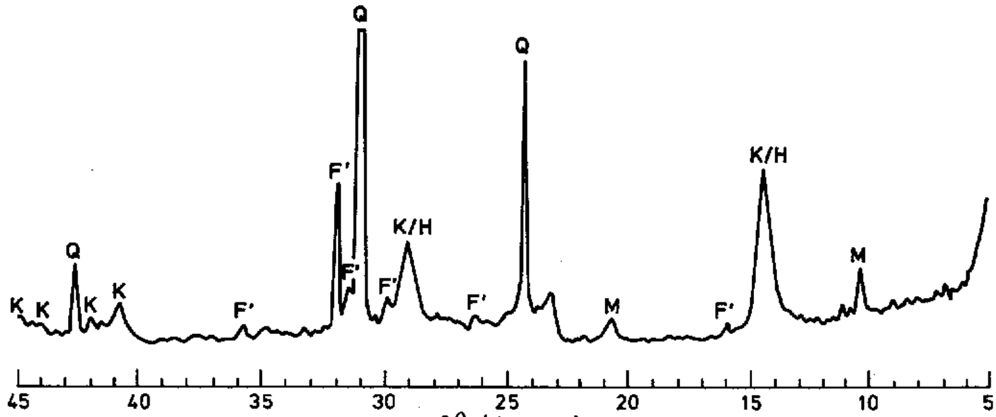
| | | | |
|---|---|---|---|
| Q | Quartz | H | Halloysite |
| F | Feldspar (alkali) | K | Kaolinite |
| M | Muscovite/Illite | C | Chlorite |
| Gi | Gibbsite | G | Goethite (?) |

Note : XRD traces are from Hencher (1990). Peaks identified by T.Y. Irfan & I.R. Basham.

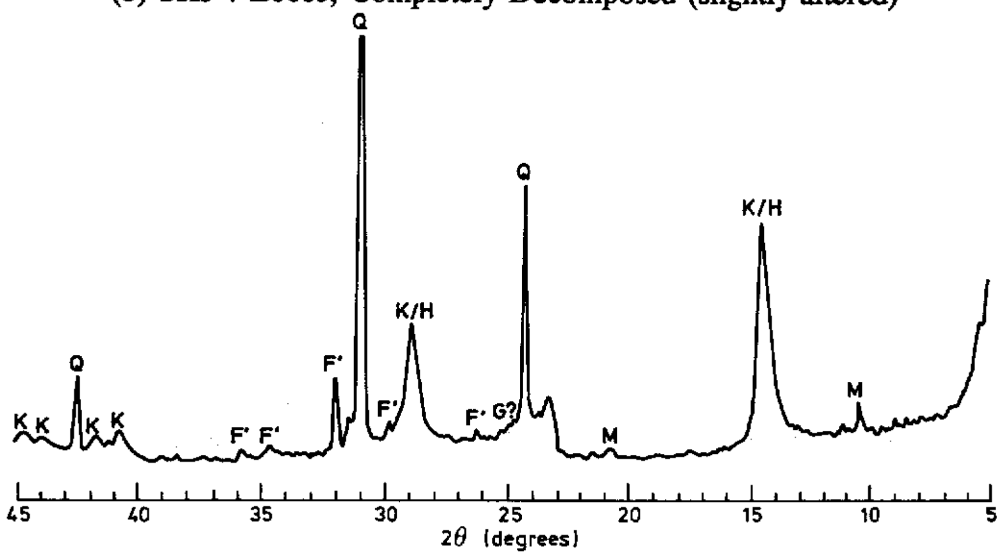
Figure 6 - Selected Results of XRD Analyses on Bulk Specimens of Soil Grades of Weathered Granite, Shouson Hill




(a) SH8 : Loose, Completely Decomposed




(b) SH5 : Loose, Completely Decomposed (slightly altered)



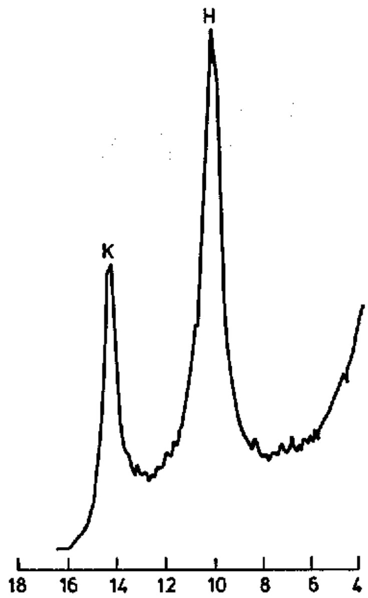

(c) SH3 : Transition Granitic Soil

Legend :

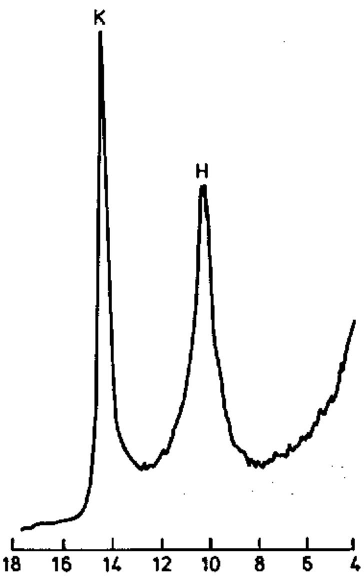
| | | | |
|---|---|---|---|
| Q | Quartz | H | Halloysite |
| F' | Alkali feldspar | K | Kaolinite |
| M | Muscovite/Illite | G | Goethite |

Figure 7 - Selected Results of XRD Analyses on Bulk Specimens of Soil Grades of Weathered Granite, Shouson Hill

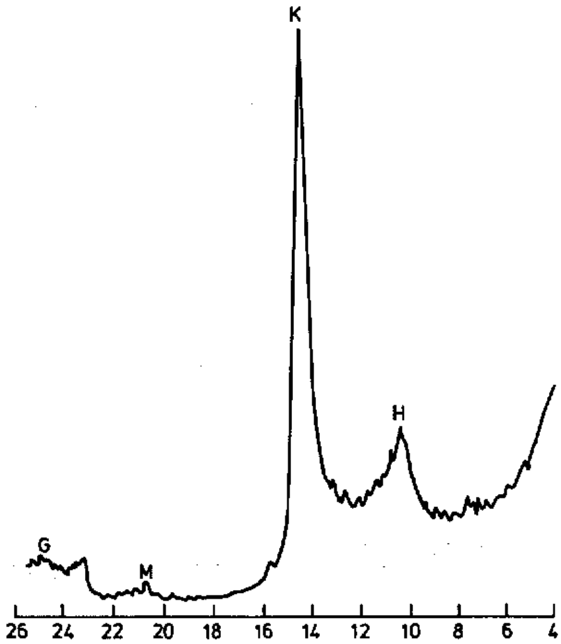

(a) SH8 : Loose Completely Decomposed




(b) SH5 : Loose Completely Decomposed (slightly altered)




(c) KP2 : Completely Decomposed (Altered)

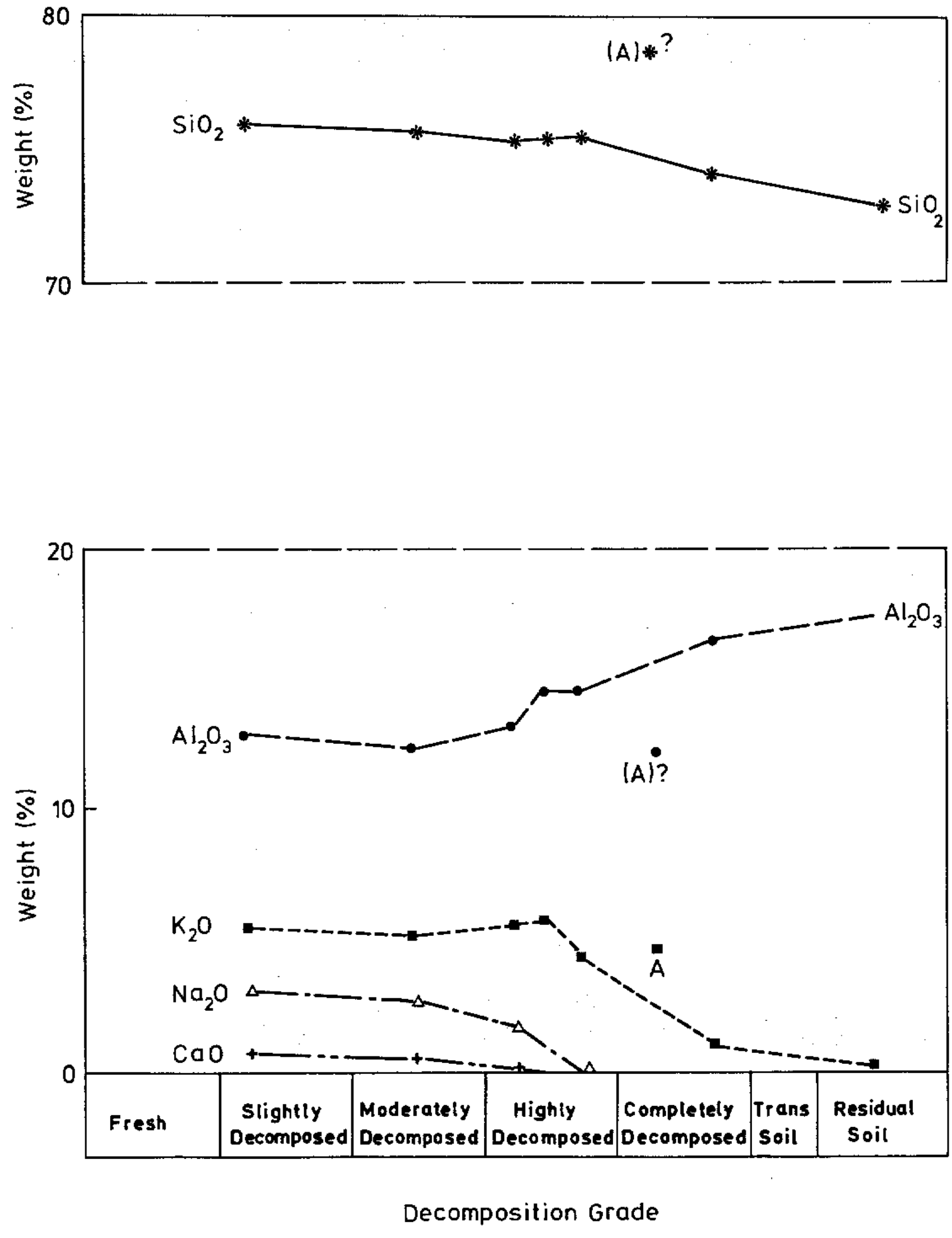



(d) SH3 : Transition Soil

Legend :

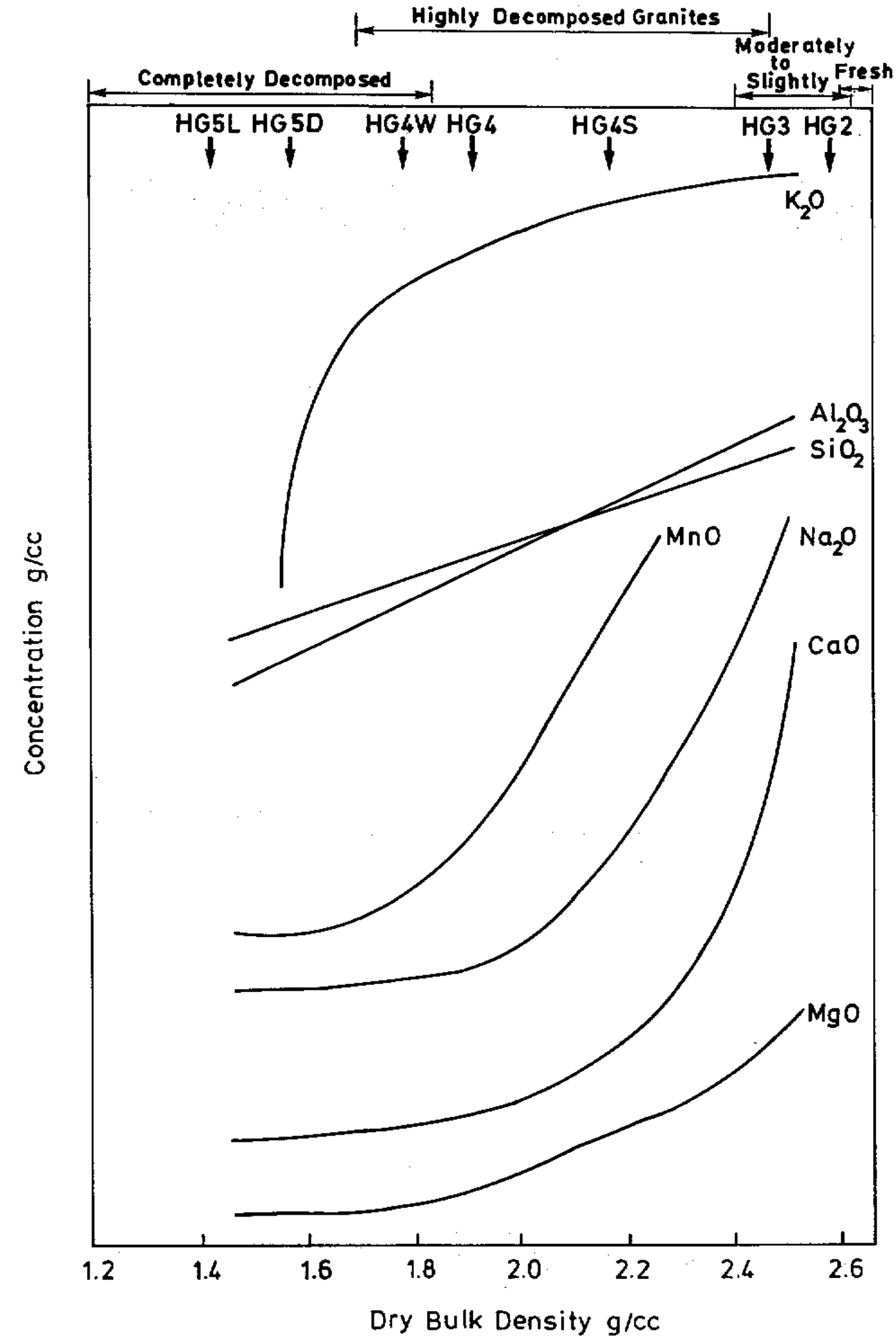
| | | | |
|---|---|---|---|
| K | Kaolinite | M | Muscovite |
| H | Halloysite | G | Goethite |

Figure 8 - XRD Patterns of Formamide-treated Completely Decomposed Granite Specimens



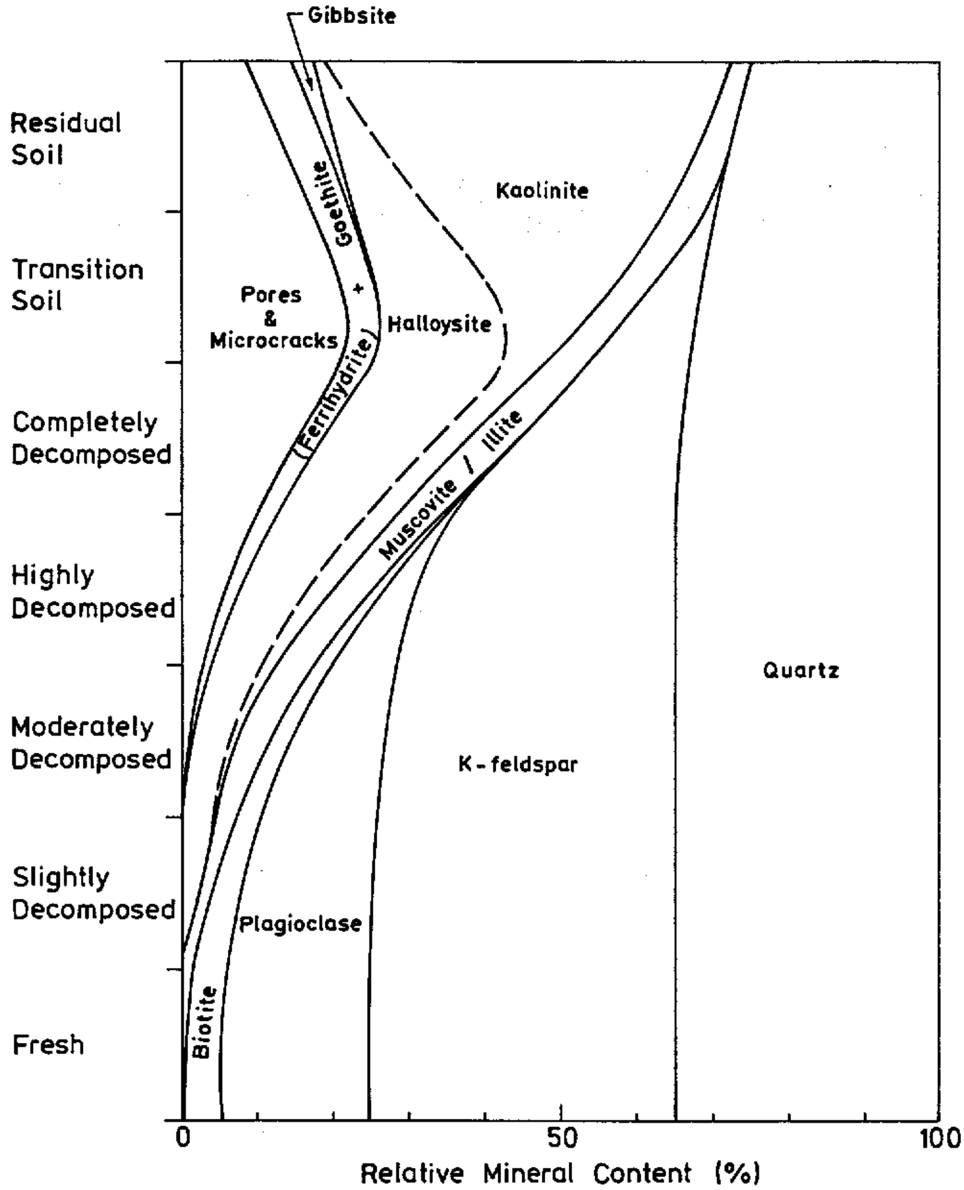

A-Altered specimen

Figure 9 - Schematic Representation of Variation in Major Oxides Contents in Granite with Weathering (Constant Weight Conditions)




Notes :
(1) Vertical scales are different for different oxides and their positions do not reflect their relative concentrations.
(2) Ranges of dry density for different weathering grades of granite are based on in-house test results, Dearman & Irfan (1978) and Gamon (1986).
(3) Chemical results are for Shouson Hill granite samples analysed by Hencher (1990).

Figure 10 - Schematic Representation of Variation in Major Oxides Contents in Granite with Weathering (Constant Volume Conditions)




Notes :

(1) Variations in mineralogy are likely to occur in each grade, resulting from variations in the composition of the fresh granite (e.g. biotite content may be up to 20% in some granites).

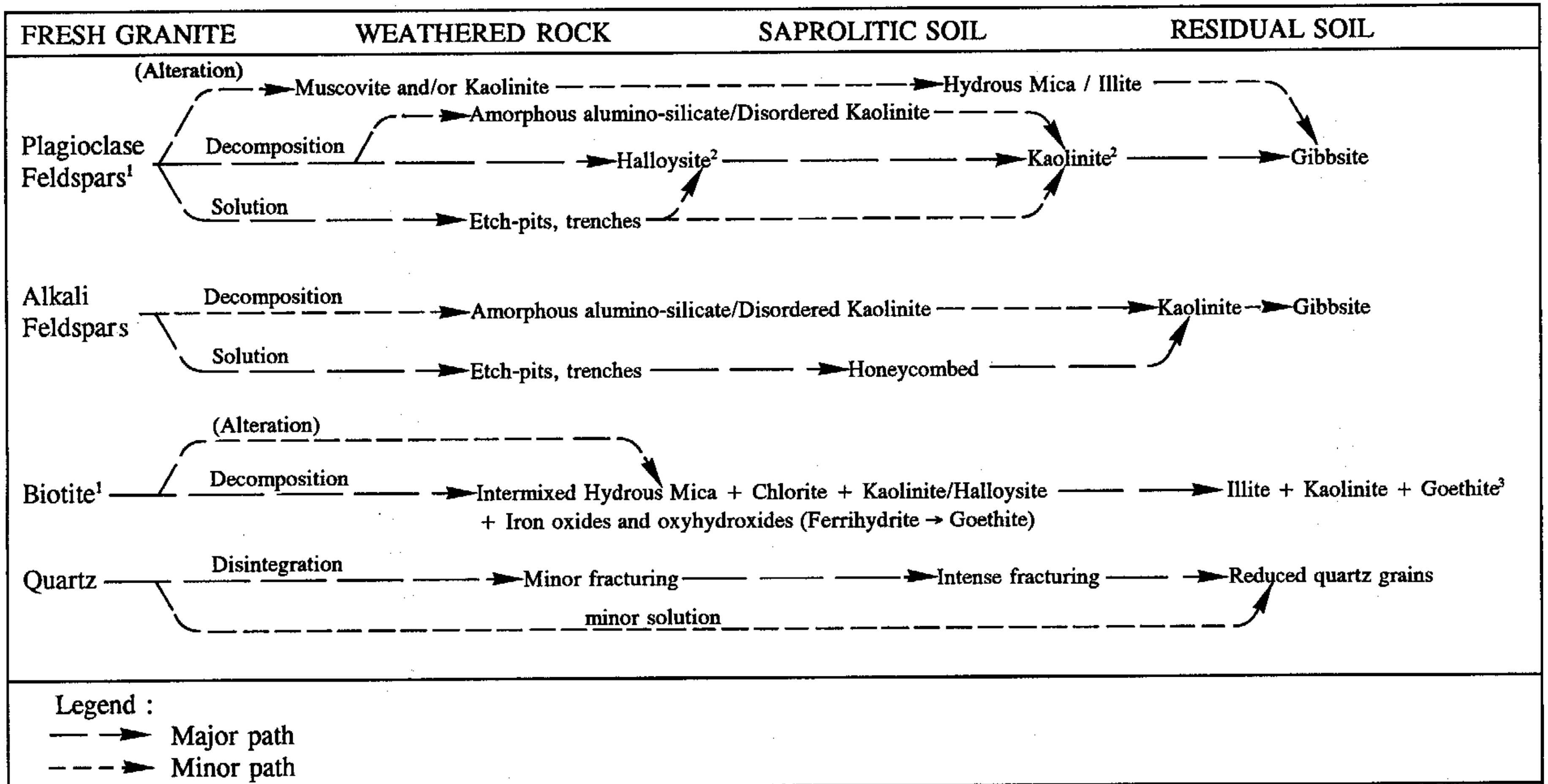
(2) In rocks affected by hydrothermal alteration different mineral assemblages or proportions may occur depending on the intensity of alteration.

(3) Proportions of clay and micaceous minerals and pores / microcracks in the highly and particularly in the completely decomposed granite grades can be very variable depending on the degree of disintegration and decomposition, the intensity of hydrothermal alteration and the microenvironment of weathering (e.g. leaching conditions). Other clay minerals, e.g. smectite, may also form in poorly drained sites.

(4) The terms muscovite / illite are used for fine grained micaceous products. Sericite is sometimes used in the literature to describe these products. Muscovite may also be present in small amounts as a primary mineral in granites.

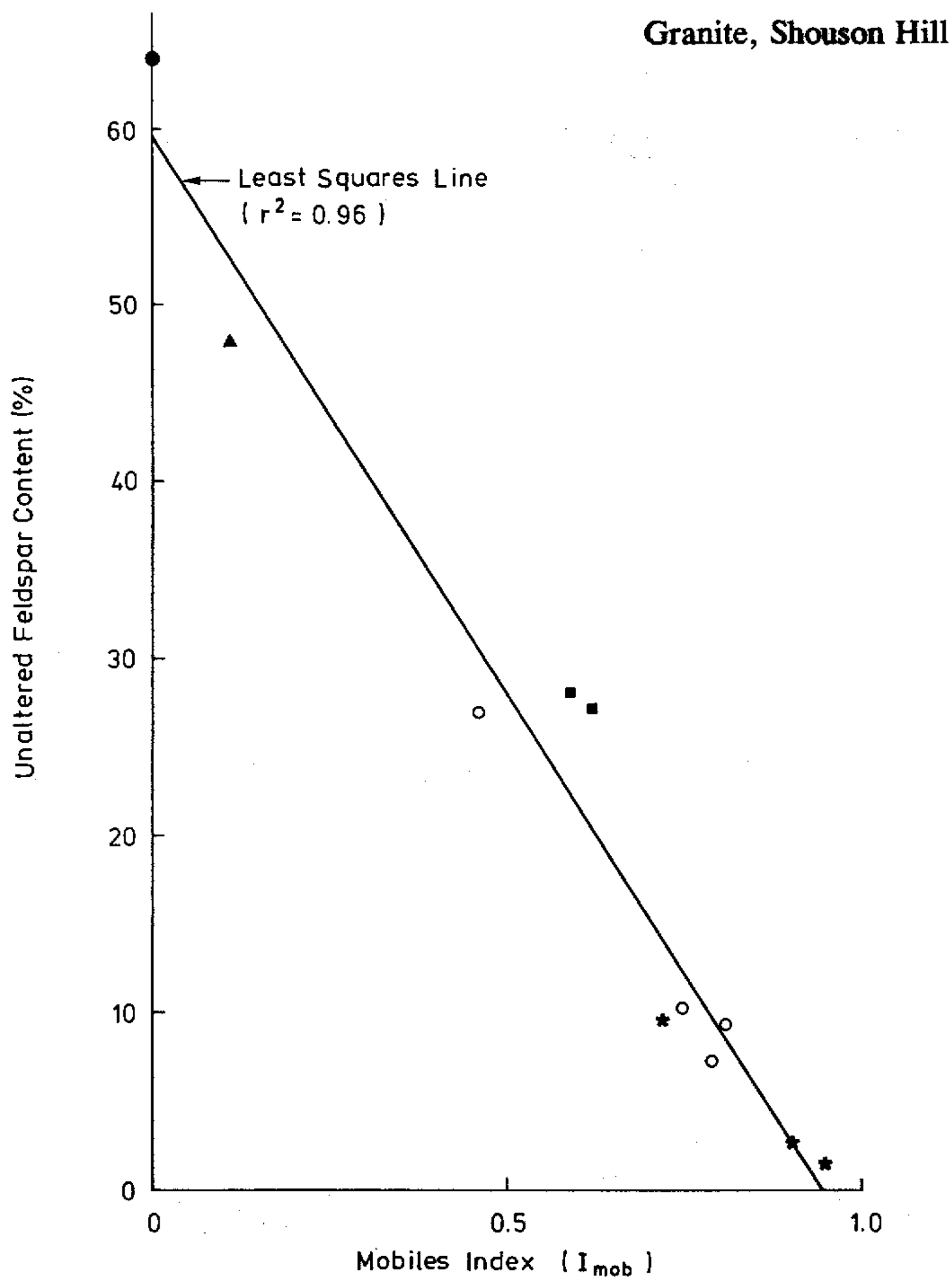
(5) Hematite may also be present if fresh rock contains magnetite.

Figure 11 - Variation in Mineralogical and Pore Composition of Granite with Weathering (Based on Granite from Shouson Hill)




Notes : (1) Fine-grained hydrous mica (commonly termed sericite) is invariably present in plagioclase even in the fresh granite, formed from late-stage magmatic and hydrothermal alteration. Biotite may also be partially altered to chlorite and a variety of secondary products by hydrothermal alteration.
(2) In poorly-drained sites, other mineral transformations may also be possible (e.g. feldspar → smectite).
(3) Hematite may also be formed if original rock contains magnetite.

Figure 12 - Possible Paths of Transformations of Primary Minerals in Hong Kong Granites with Weathering

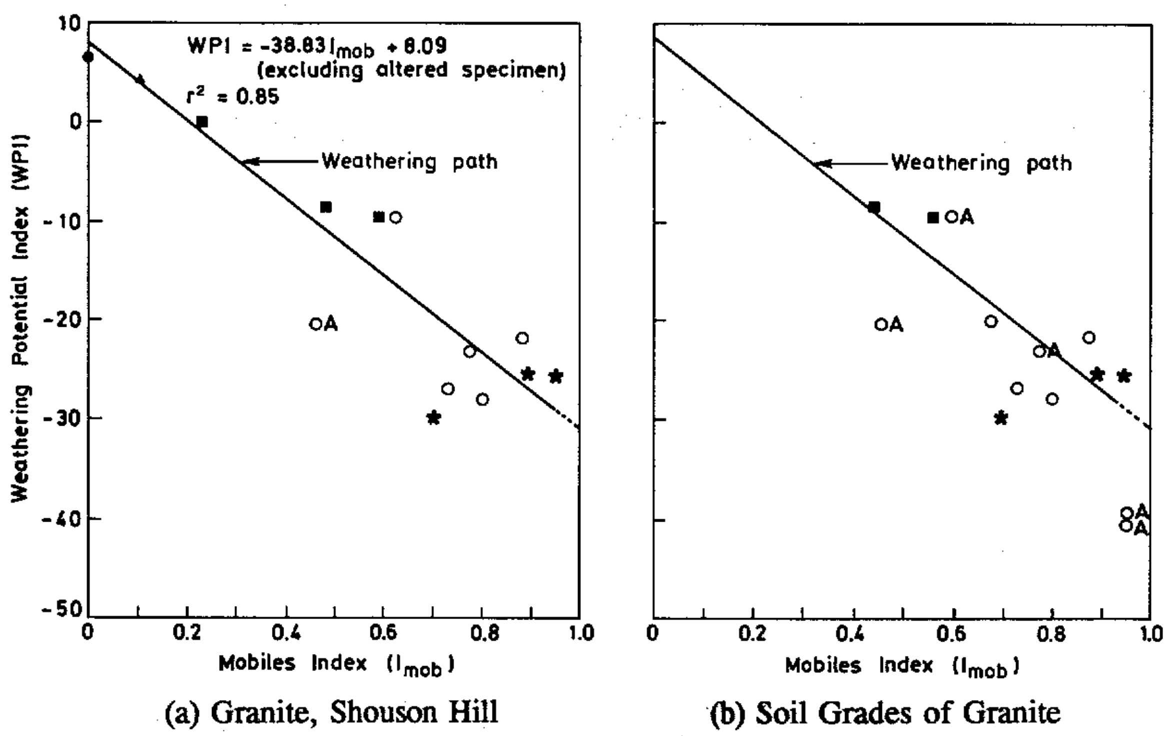



Legend :

| | | | |
|---|---|---|---|
| * | Transition Soil/Residual Soil | ▲ | Moderately Decomposed |
| o | Completely Decomposed | ● | Fresh to Slighly Decomposed |
| ■ | Highly Decomposed | | |

Note : Mobiles index does not equal to 1.0 for zero feldspar content due to the presence of mobile cation-bearing clay minerals in residual soil.

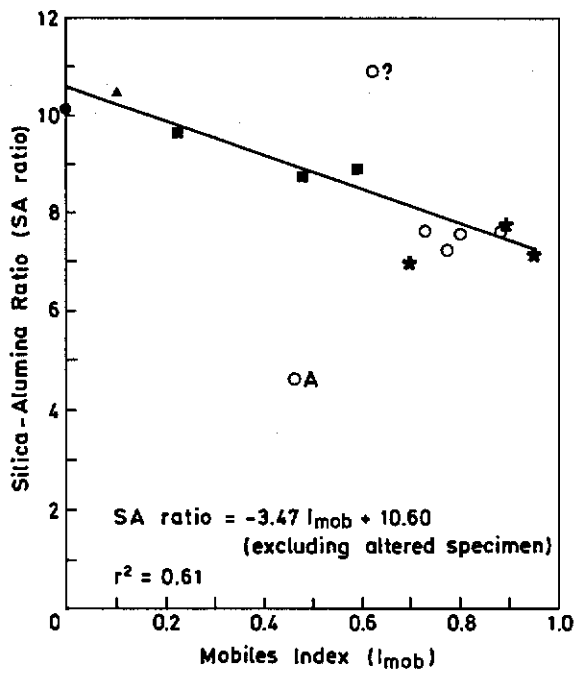
Figure 13 - Unaltered Feldspar Content versus Mobiles Index




Legend :

| | | | |
|---|---|---|---|
| * | Transition Soil/Residual Soil | ▲ | Moderately Decomposed |
| ○ | Completely Decomposed | ● | Fresh to Slighly Decomposed |
| ■ | Highly Decomposed | A | Hydrothermally altered |

Figure 14 - Mobiles Index versus Weathering Potential Index

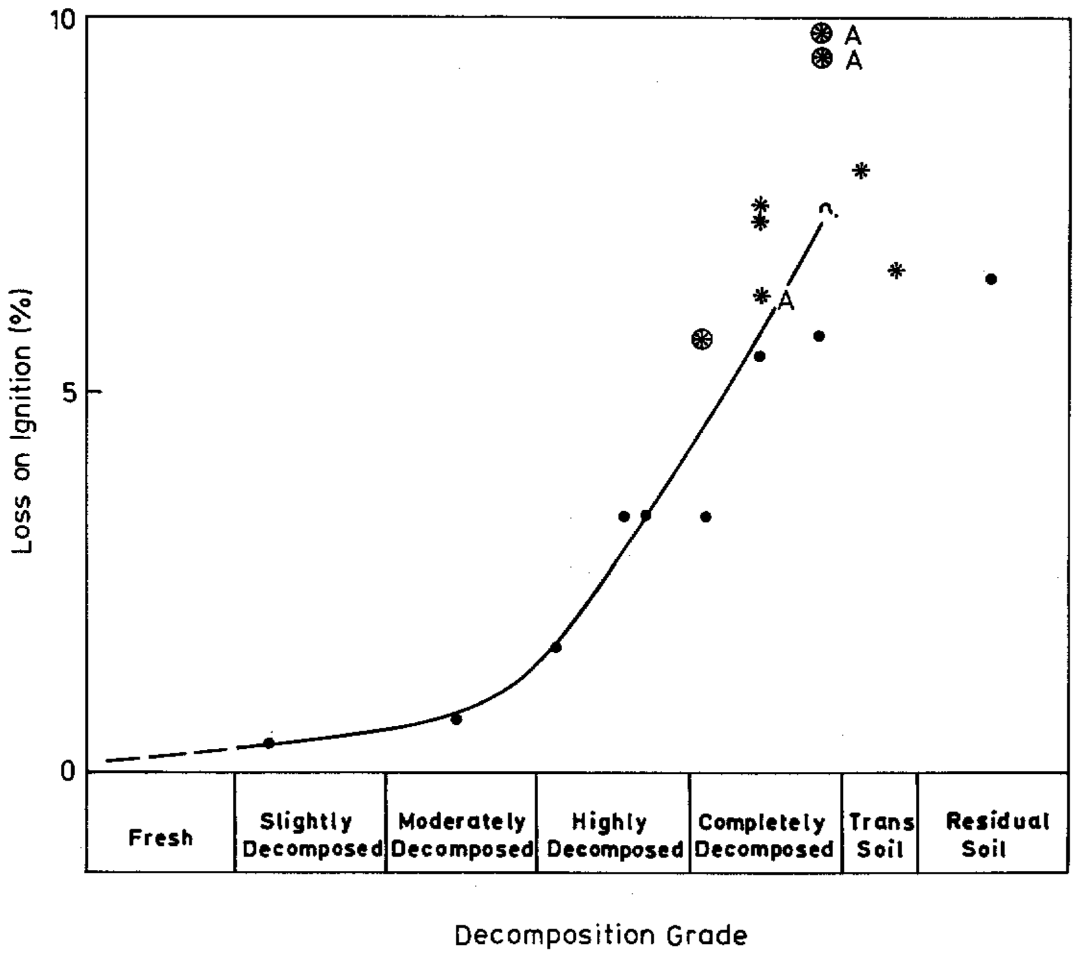



Granite, Shouson Hill

Legend :

| | | | |
|---|---|---|---|
| * | Transition Soil/Residual Soil | ▲ | Moderately Decomposed |
| o | Completely Decomposed | • | Fresh to Slighly Decomposed |
| ■ | Highly Decomposed | A | Hydrothermally altered |

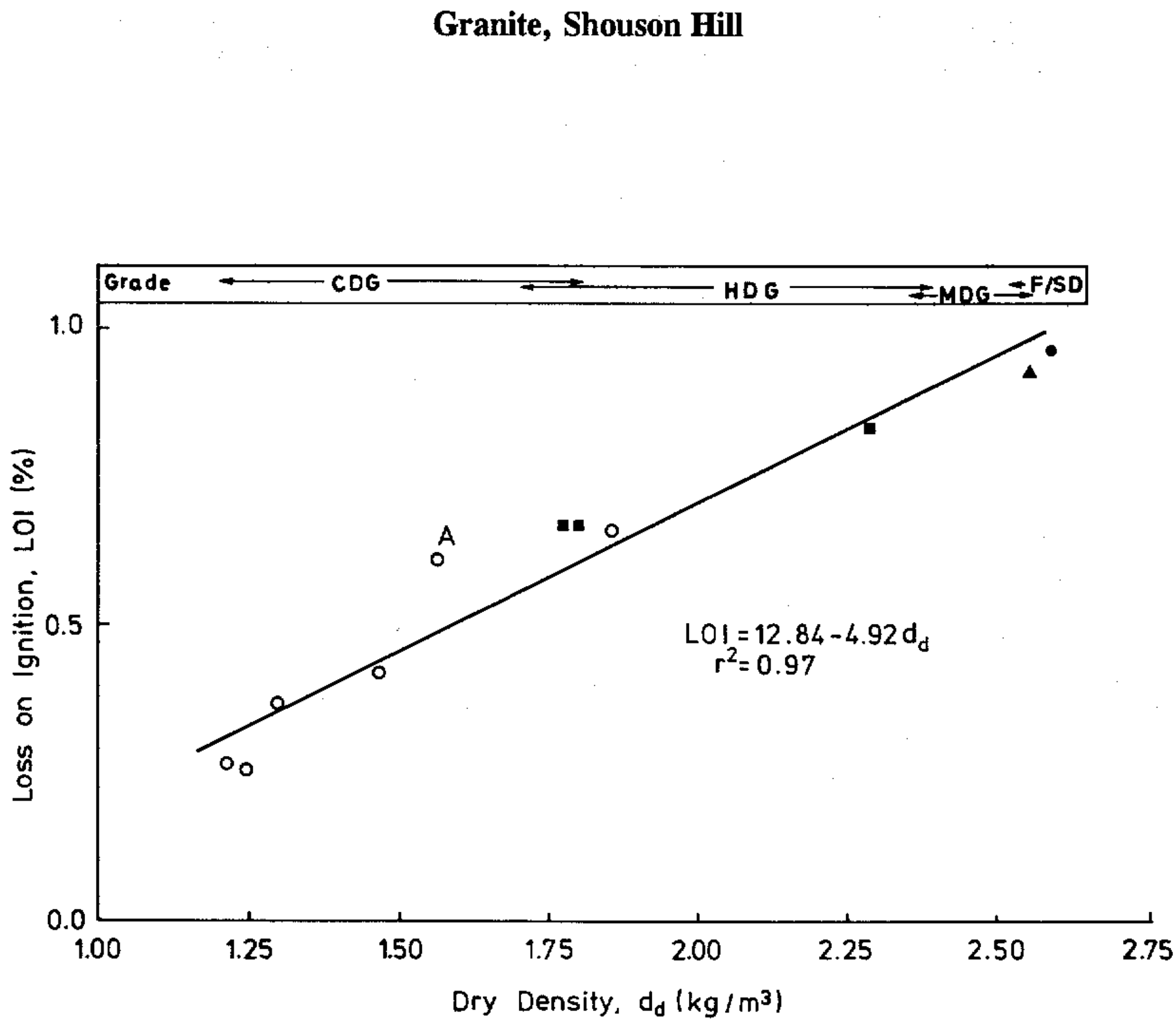
Figure 15 - Mobiles Index versus Silica-Alumina Mole Ratio




Legend :

- ✱ Other Laboratories } Shouson Hill Granite
- ● Results by Leeds University } Shouson Hill Granite
- A Hydrothermally Altered
- O King's Park/Homantin Granite

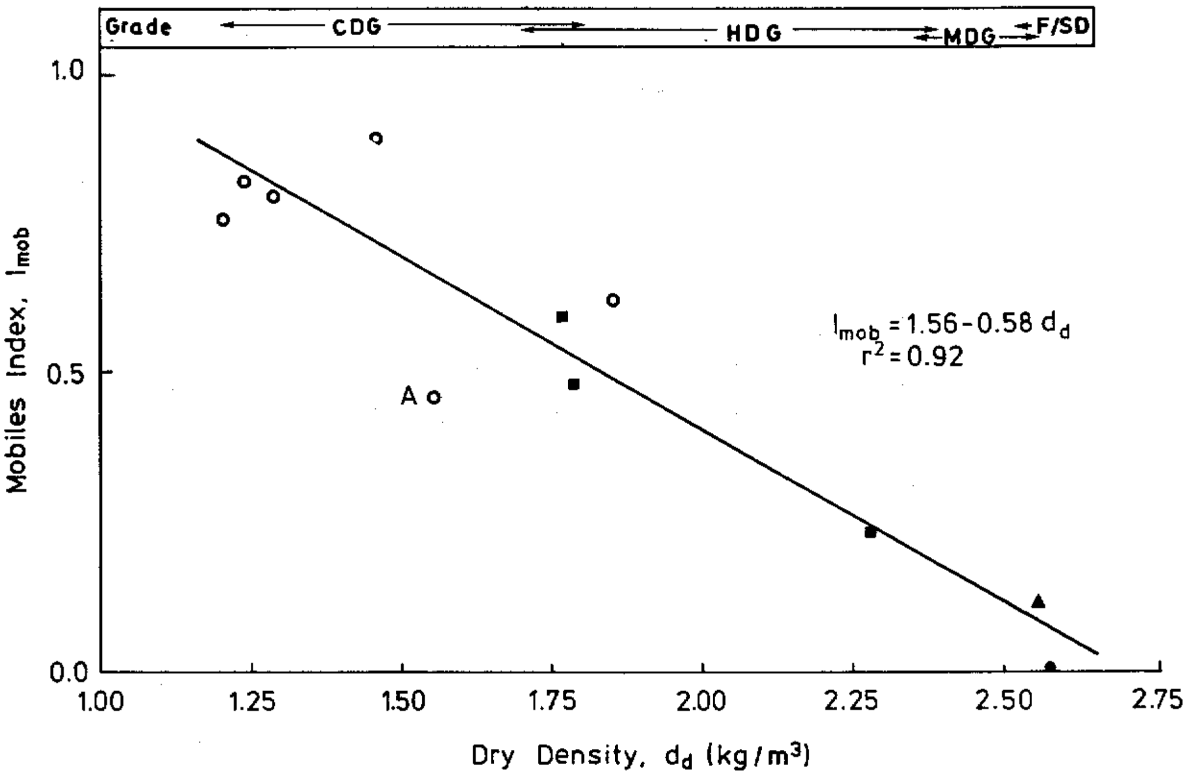
Figure 16 - Loss on Ignition Value versus Decomposition Grade




Notes : (1) Transition Soil and Residual Soil specimens not shown.
(2) Altered specimen excluded from the least square analysis.

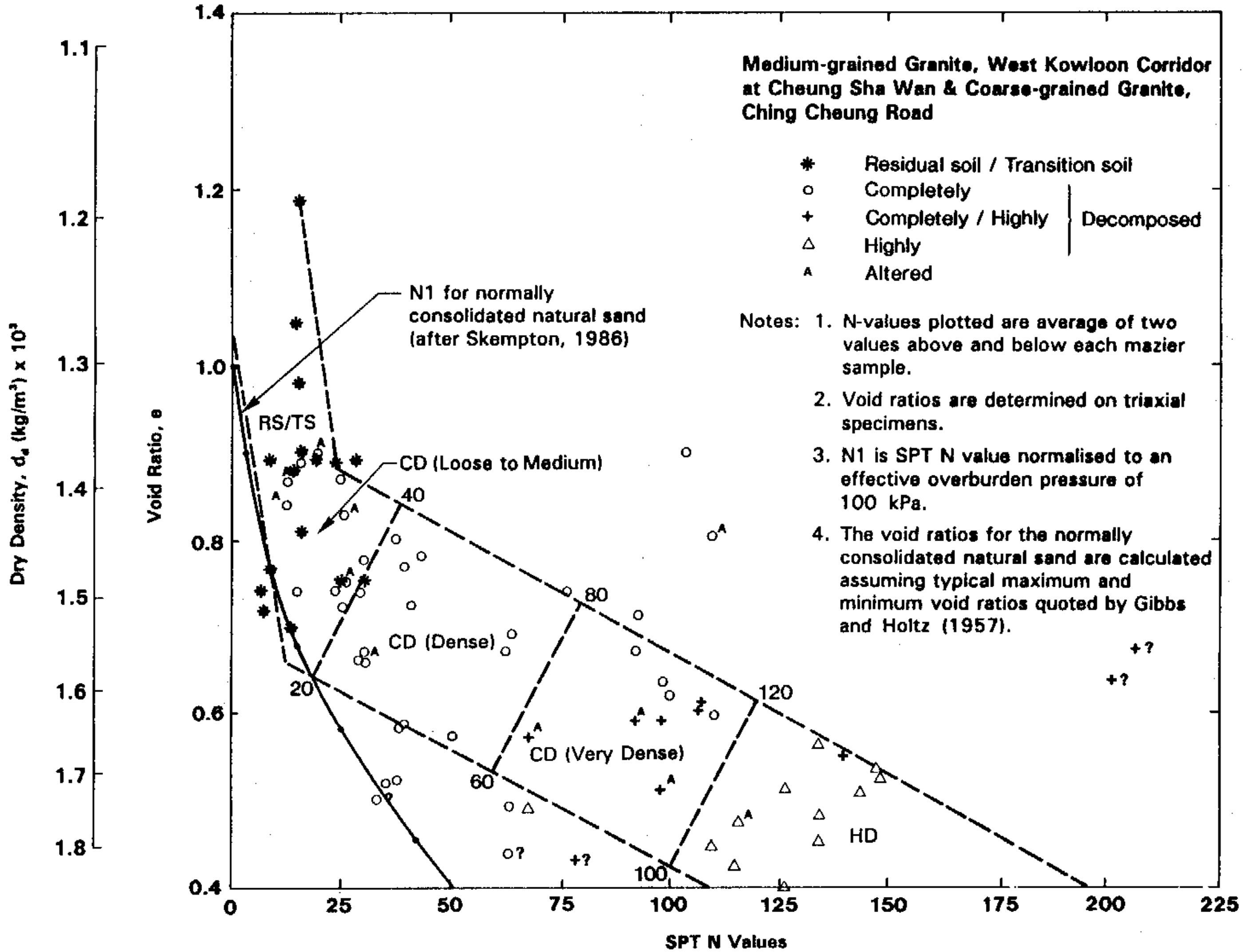
Figure 17 - Loss on Ignition Value versus Dry Bulk Density

Granite, Shouson Hill




Notes : (1) Transition Soil and Residual Soil specimens not shown.
(2) Altered specimen excluded from the least square analysis.

Figure 18 - Mobiles Index versus Dry Bulk Density




Relationship between SPT N Value and Void Ratio

Figure 19 - Classification of Soil Grades of Weathered Granite in terms of Dry Bulk Density, Void Ratio and SPT Values

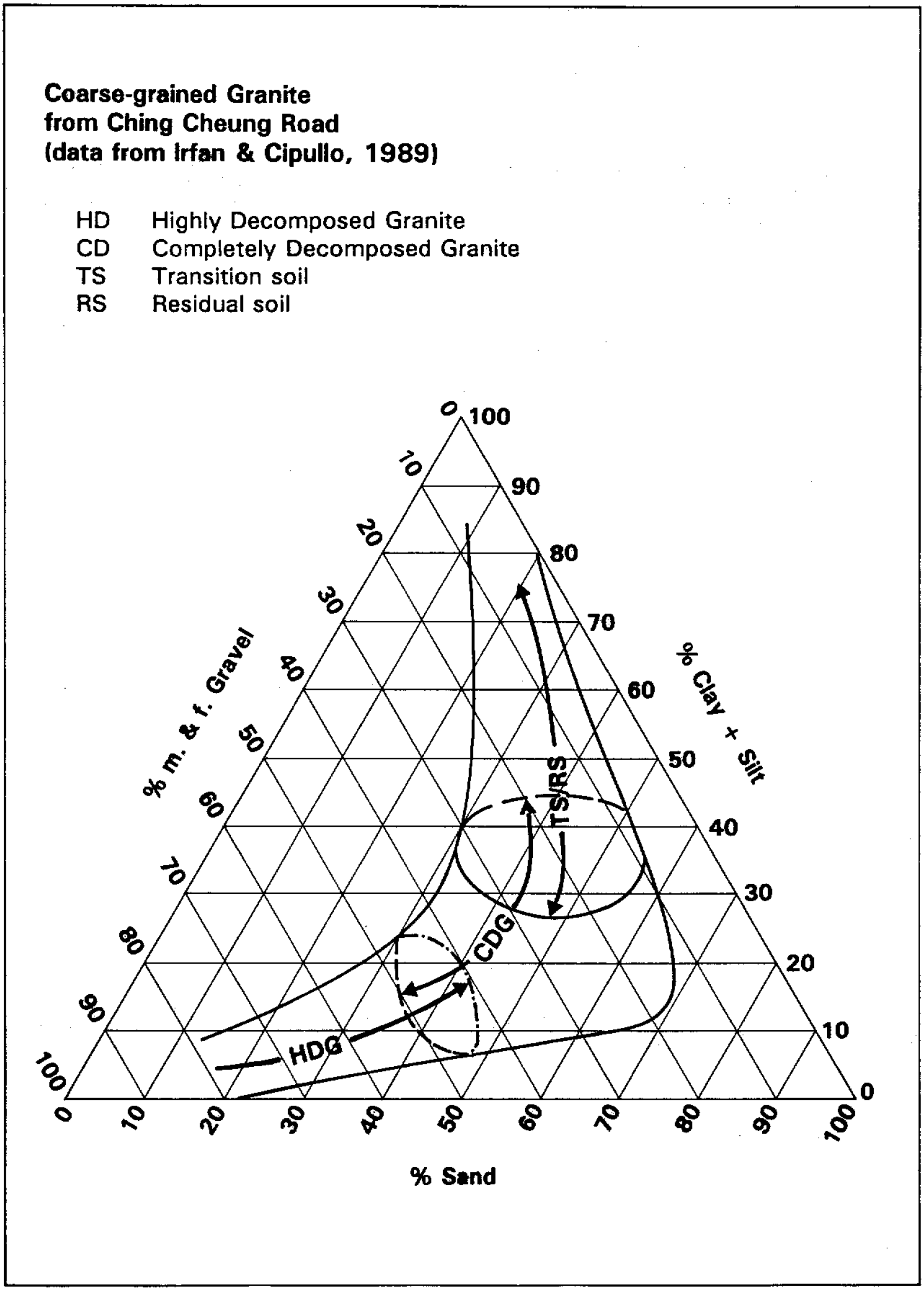



Figure 20 - Effect of Weathering on Particle Size Distribution of a Coarse-grained Granite (Data from Irfan & Cipullo, 1989)

## LIST OF PLATES

Negative No. : SP 93/212/1A&3A

Plate 1 - Weathering Profile in Medium-grained Granite, East Kowloon

Negative No. : SP 93/214/3

Plate 2 - Complex Weathering Profile in Fine- to Medium-grained Granite Affected by Faulting, Dyke Intrusion and Alteration, Jordan Valley

Negative No. : SP 93/214/1

Plate 3 - Corestones in a Granitic Saprolite

Negative No. : SP 91/031/22A

Note : Basalt dyke (dark grey), centre left.

Plate 4 - Penetration of Weathering along Fault Zone and Dyke Intrusion

Negative No. : SP 97/85/2A

Negative No. : SP 97/85/5A

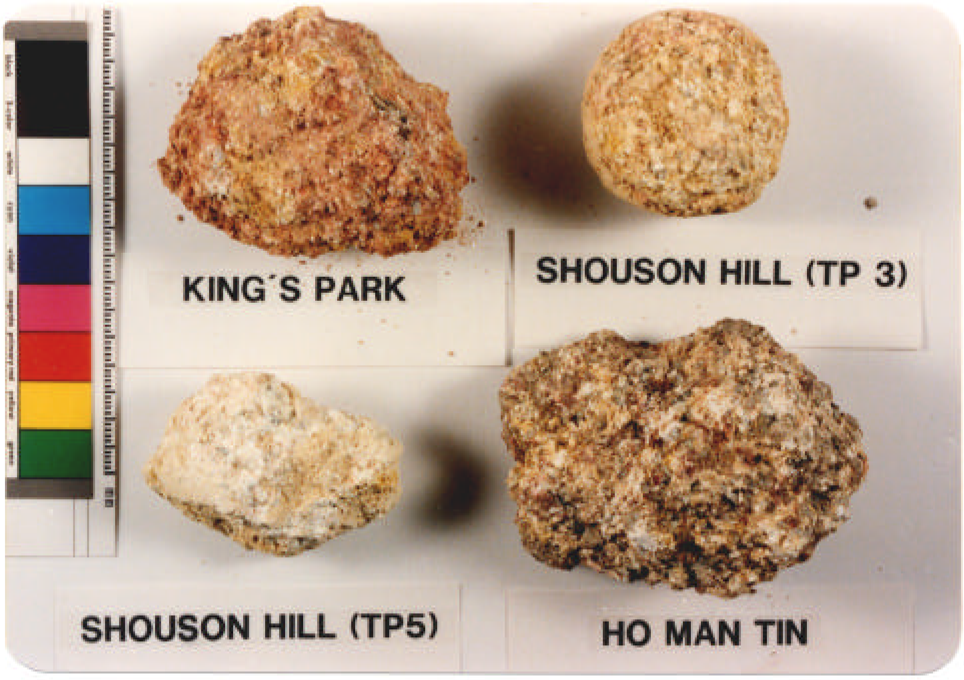
Note : White patches are hydrothermally altered, kaolinised granite.

Plate 5 - Granitic Saprolite and Residual Soil at Shouson Hill

Negative No. : SP 93/214/2

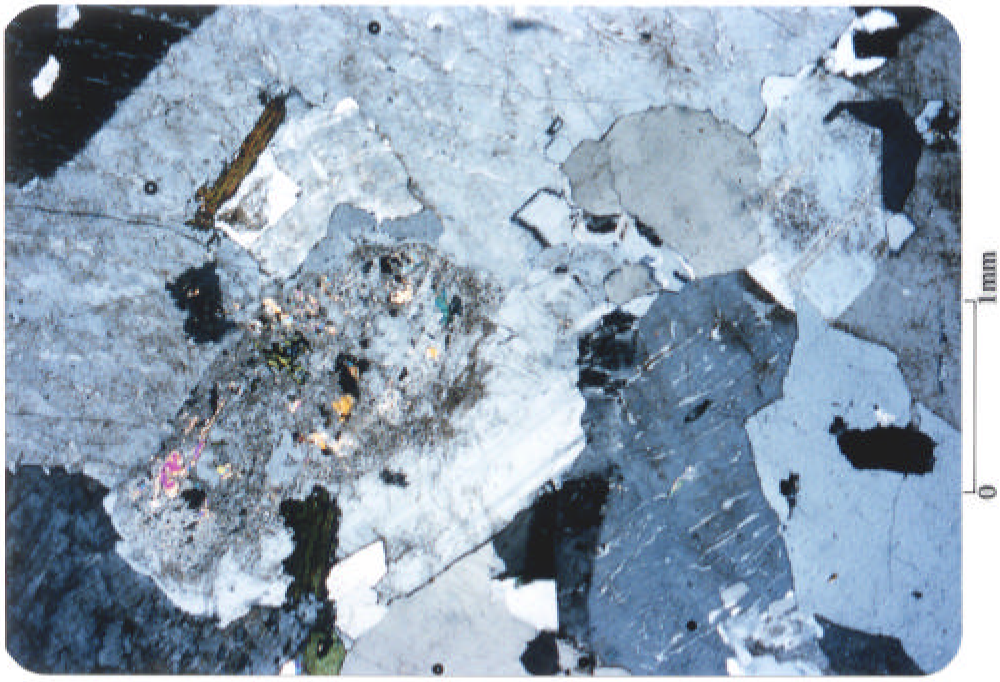
Plate 6 - Effects of Hydrothermal Alteration Adjacent to Quartz-Kaolin Veins


Plate 7 - Hand Specimens of Granite Weathered to Different Degrees

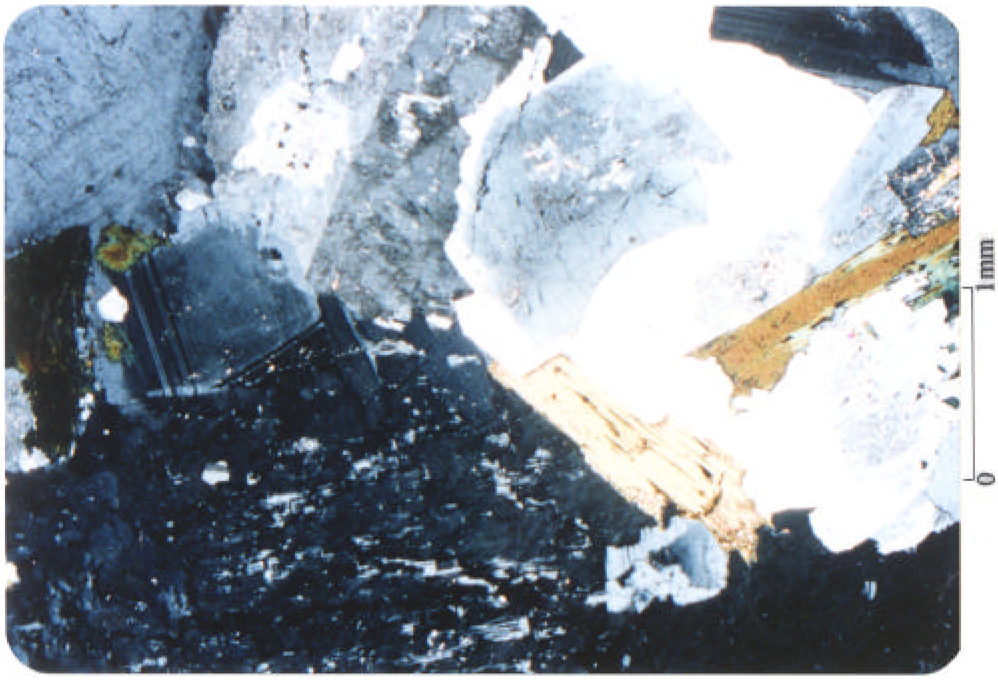



Negative No. : EG 87/14/35

Plate 8 - Variation in Completely Decomposed Granite Samples



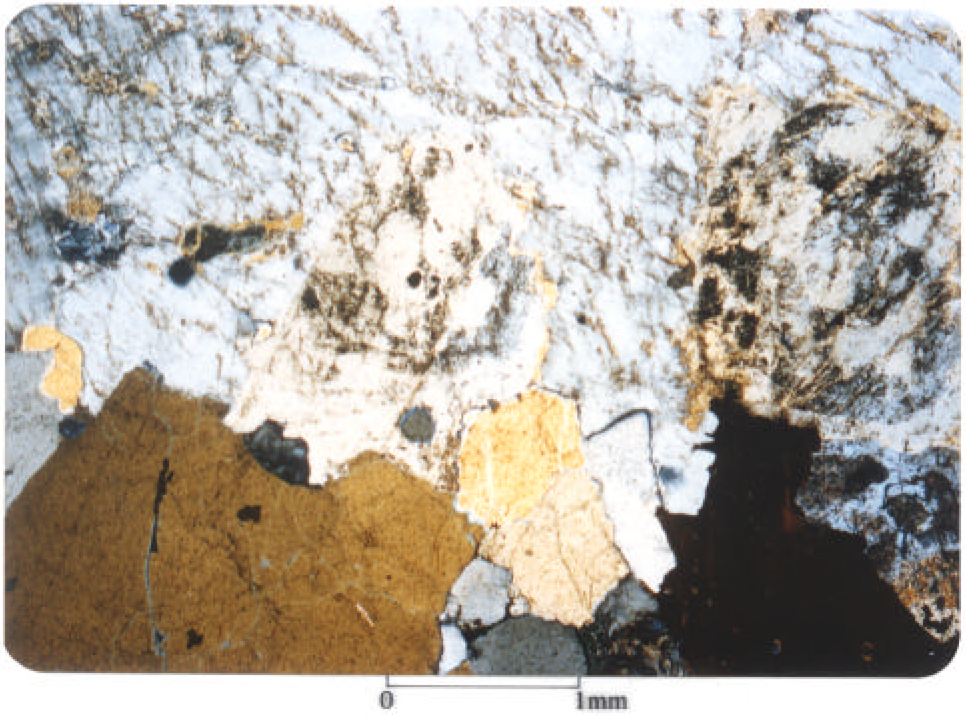

(a) Geological Survey Sample No. : 3614. Plagioclase (centre) showing sericitization; fresh alkali feldspar (streaky grey) and quartz (uniform grey or white); biotite (brown). (Cross-polarized light). Negative No. : SP 93/162/8A.



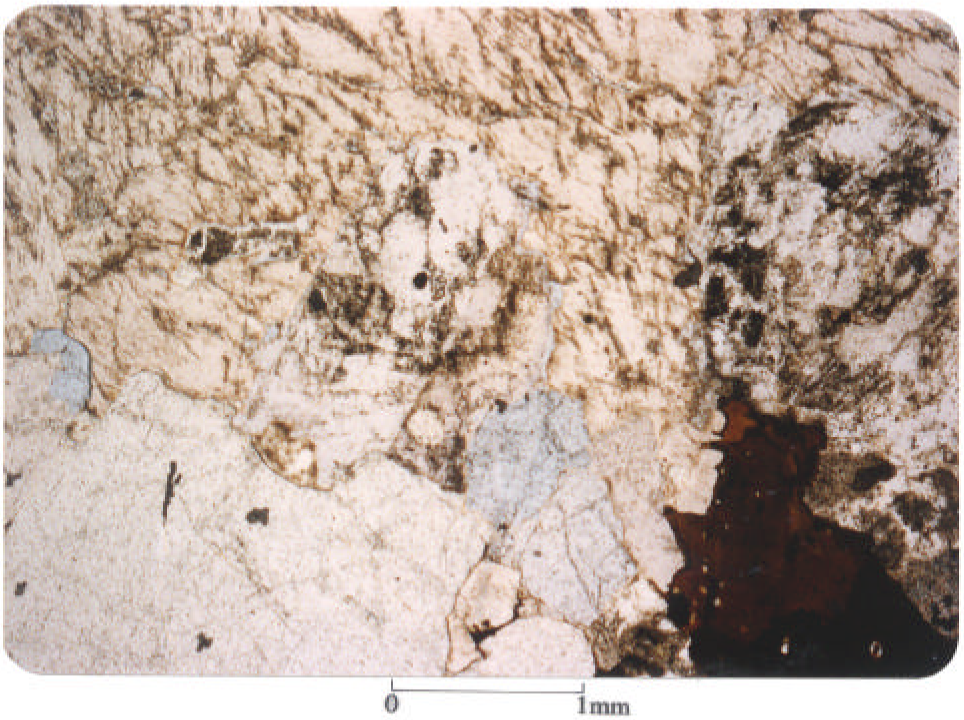

(b) Slight sericitization of plagioclases (centre and right side of photograph); slight chlorization (green) of biotite (brown, right). Negative No. : SP 93/159/0.

Note : Sample 404.01 from Shouson Hill (thin section provided by Dr. Smart of Glasgow University).

Plate 9 - Photomicrographs of Fresh Medium-grained Granite, Shouson Hill



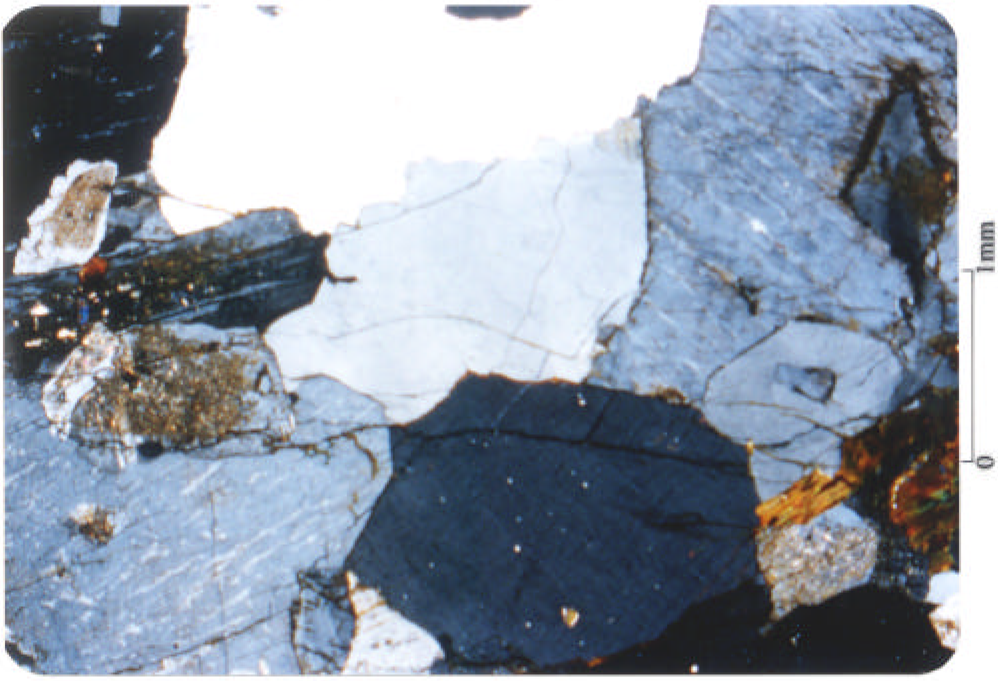
Negative No. :
SP 93/162/6A



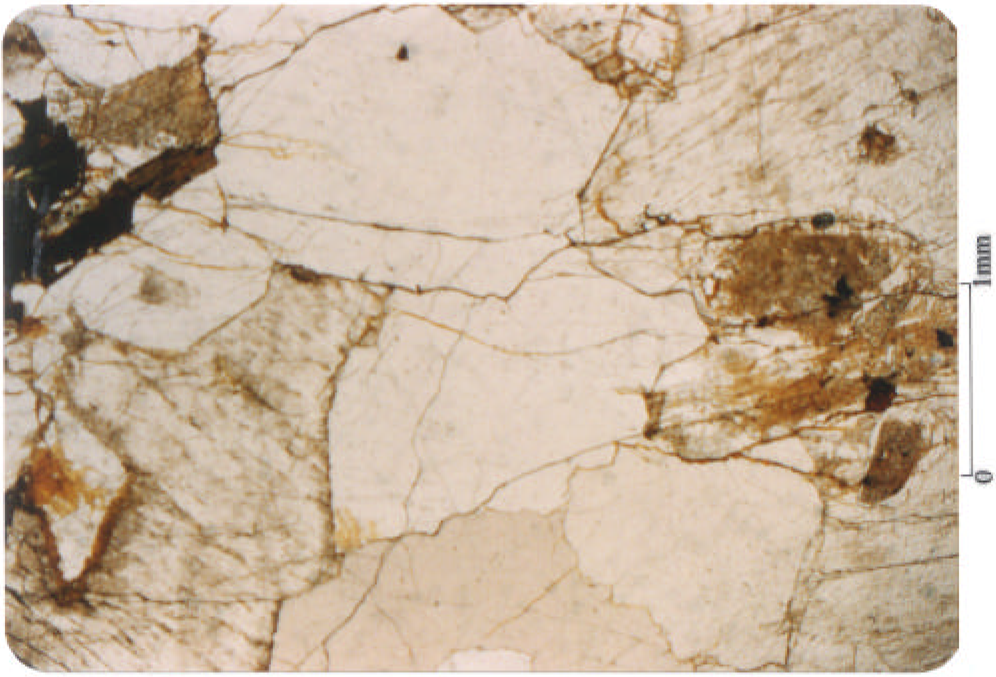
Negative No. :
SP 93/162/7A

Note : Alkali feldspar megacryst (top), slightly sericitized plagioclases (centre and right), quartz (uniform colour), biotite (brown, bottom right).

Plate 10 - Photomicrographs of Fresh Megacrystic Granite, Kings's Park



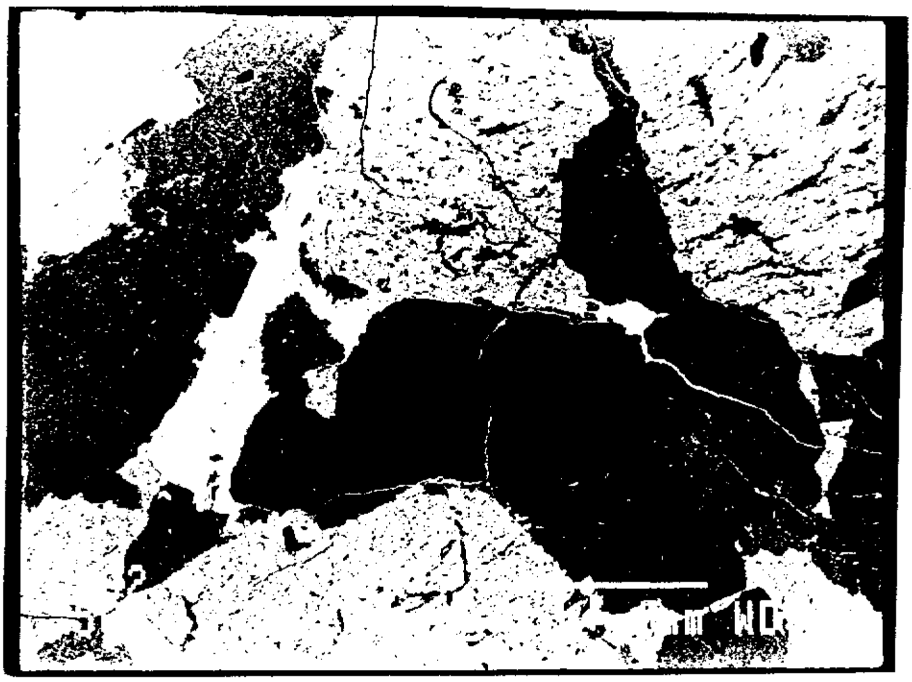

(a) Plagioclases (centre left) show increased alteration to micaceous minerals. Alkali feldspars are fresh. Rock fabric is microfractured by tight, stained, simple microcracks. (Cross polarized light). Negative No. : **SP 93/159/4.**



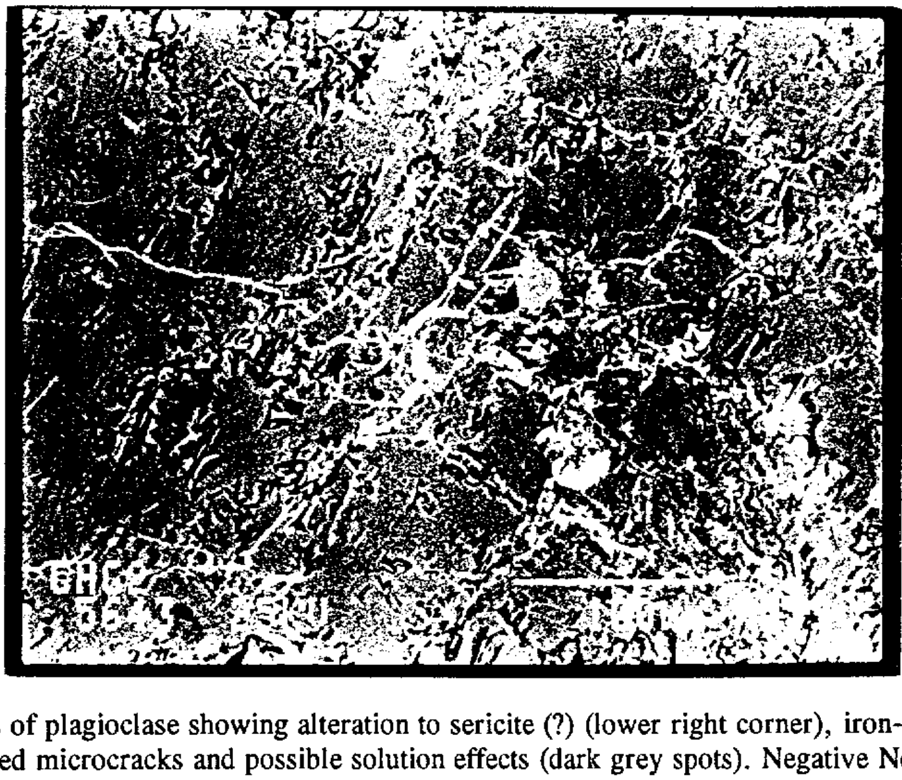

(b) Most grain boundaries are stained by iron-oxide indicating microfracturing and/or solution. (Plane polarized light). Negative No. : **SP 93/159/5.**

Note : Sample 404.02 from Shouson Hill (thin section supplied by Dr. Smart of Glasgow University).

Plate 11 - Photomicrographs of Stained Rim of Slightly Decomposed Granite



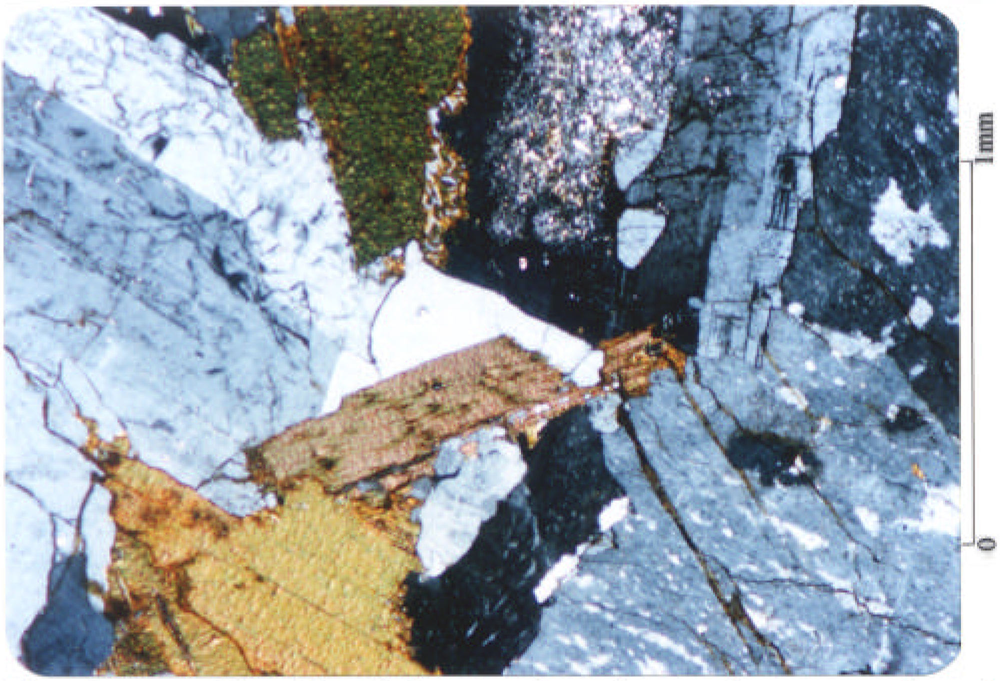
(a) Details of fabric in the stained rim of slightly decomposed granite, showing occasional tight but stained (white) microcracks cutting across quartz (dark grey) and alkali feldspars (patchy medium grey). Biotite (centre left) shows slight alteration. Negative No. : SP 93/167/11.



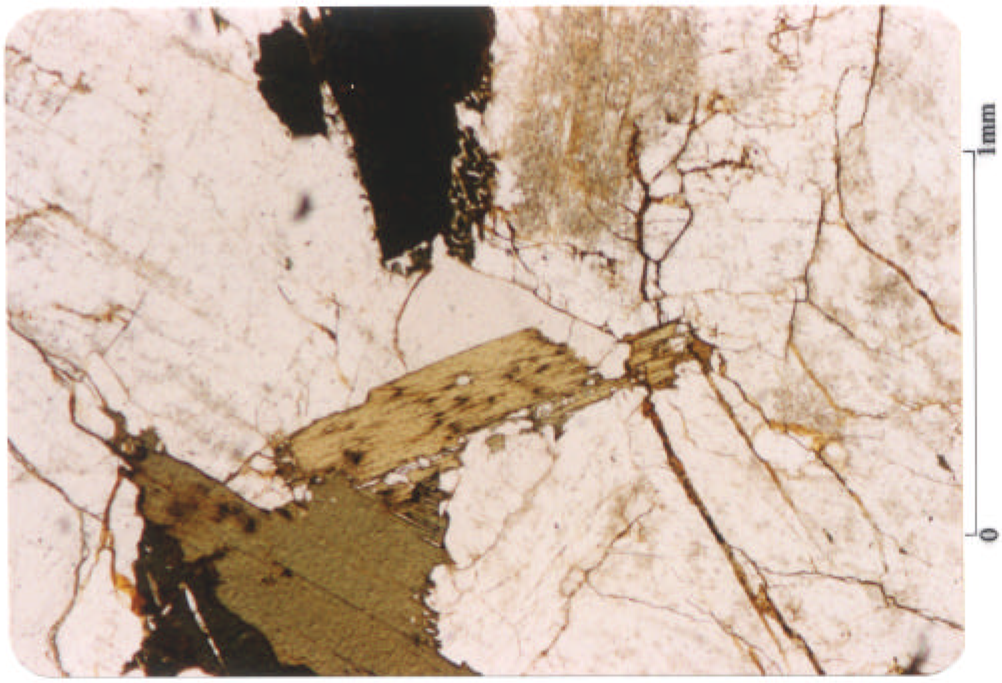
(b) Details of plagioclase showing alteration to sericite (?) (lower right corner), iron-oxide filled branched microcracks and possible solution effects (dark grey spots). Negative No. : SP 93/167/9.

Note : Sample SHS12 from Shouson Hill (photographs provided by Dr. L. Dobereiner).

Plate 12 - SEM Images of Slightly Decomposed Granite




(a) Plagioclase (top centre) is moderately decomposed to minute semi opaque growths and clay minerals; alkali feldspar (right) is unaltered but highly microfractured (see also below); biotite (top centre) shows slight alteration along grain boundary. (Cross polarized light). Negative No. : SP 93/161/21.




(b) The rock fabric is microfractured throughout by tight to slightly open, simple to complex branched, iron-oxide stained/filled microcracks. Note initiation/termination of microcracks at biotite grain (left bottom). (Plane polarized light). Negative No. : SP 93/161/22.

Note : Sample 404.03 from Shouson Hill (thin section supplied by Dr. Smart of Glasgow University).

Plate 13 - Photomicrographs of Moderately Decomposed Granite

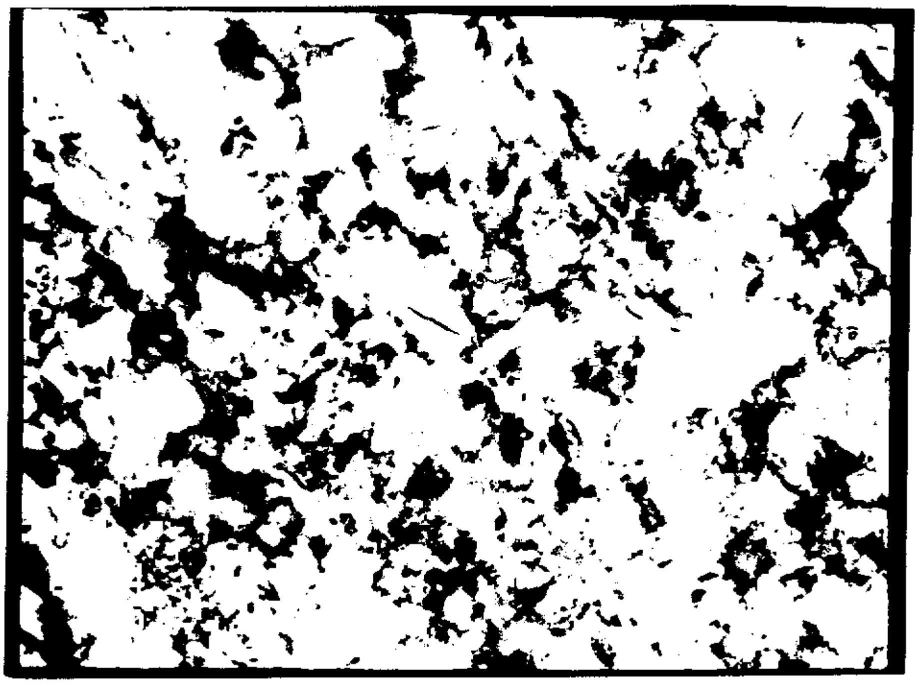
(a) Slightly open transgranular microcrack through biotite and feldspars; clay mineral growth along the biotite grain boundary and slight exfoliation of biotite (bottom left); solution features (dark grey spots) in plagioclase (centre right). Negative No. : SP 93/167/13.

(b) Large solution pores (dark grey) with iron-oxide stained walls (white) in plagioclase. Negative No. : SP 93/167/15.

Note : Sample SHS11 from Shouson Hill (photographs provided by Dr. L. Dobereiner).

Plate 14 - SEM Images of Moderately Decomposed Granite (Sheet 1 of 2)

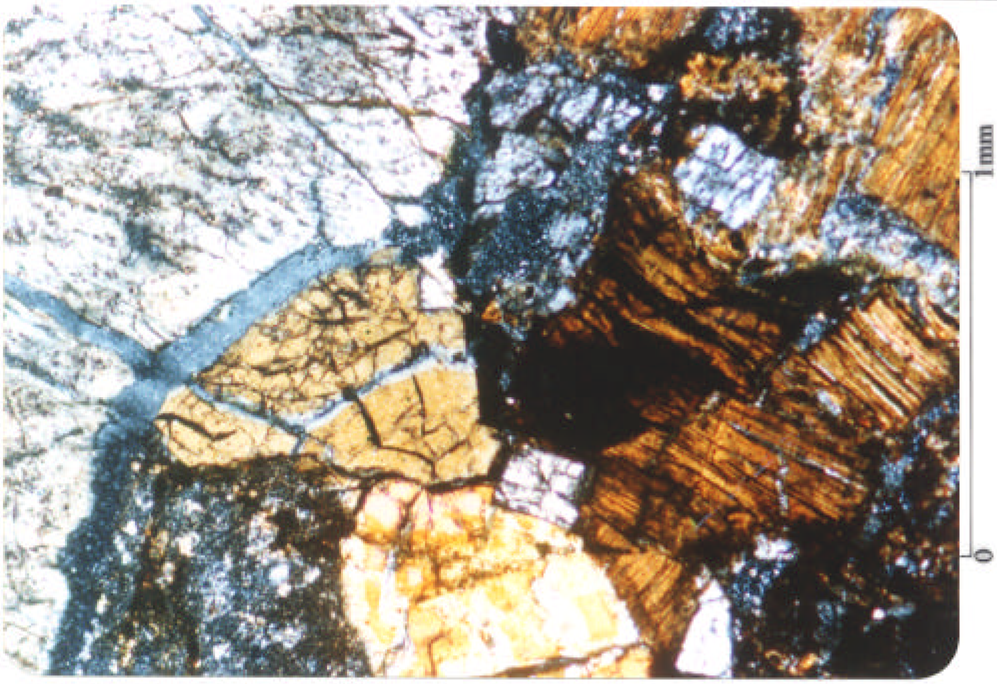
(c) Details of highly decomposed plagioclase showing numerous structure controlled, regular pattern of solution features (dark grey) and clay minerals (light grey). Negative No. : SP 93/167/17.



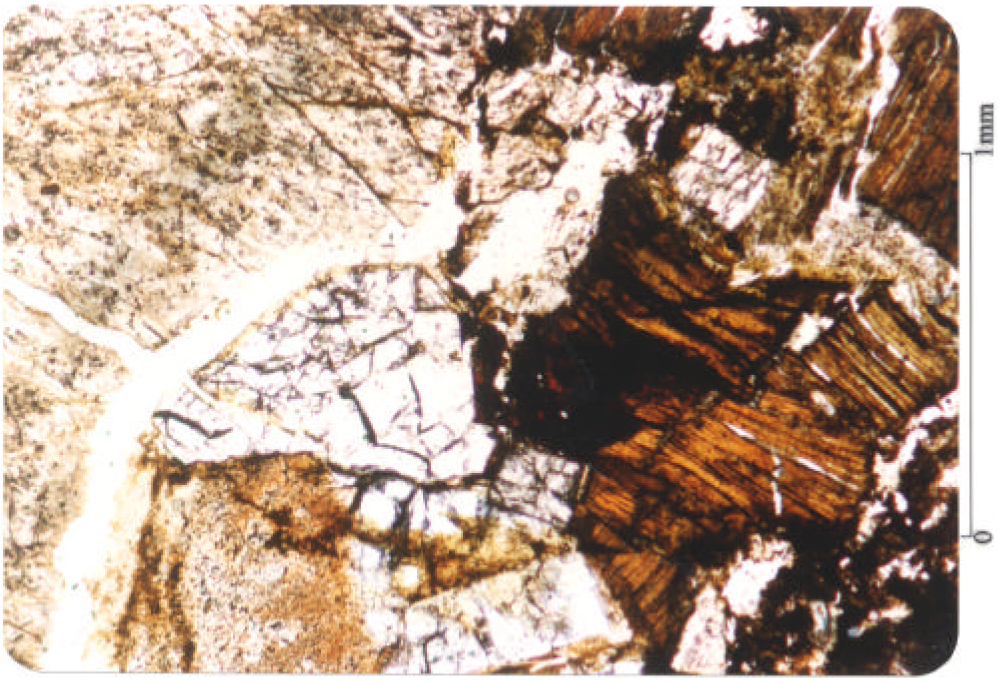
(d) Detail of (c) showing flakes of kaolinite and small pores. Negative No. : SP 93/167/19.

Note : Sample SHS10 from Shouson Hill (photographs provided by Dr. L. Dobereiner).

Plate 14 - SEM Images of Moderately Decomposed Granite (Sheet 2 of 2)



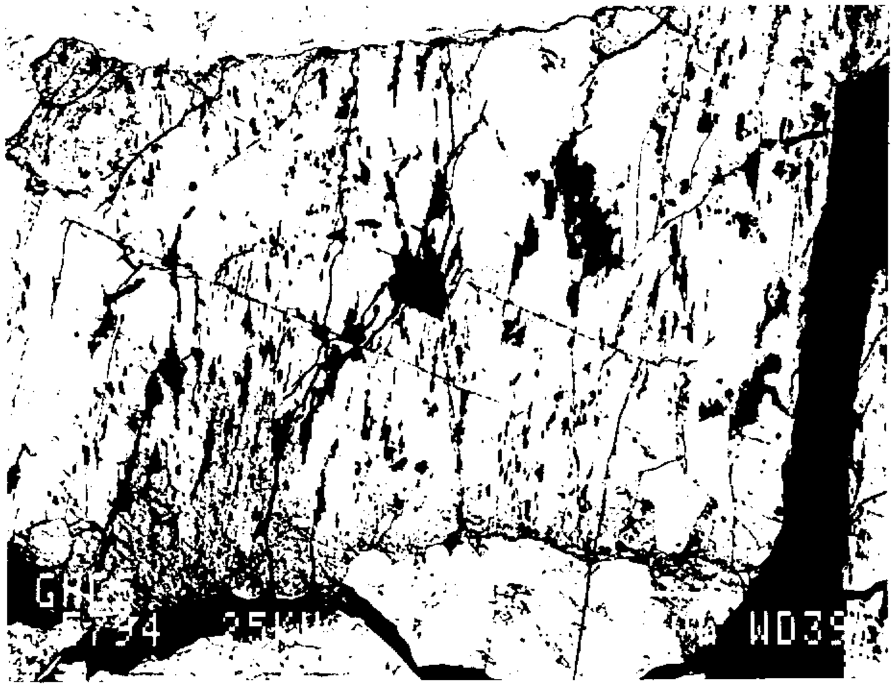

(a) Plagioclases (bottom left and top centre) are highly to completely decomposed to clay minerals; alkali feldspar (top left) shows slight decomposition and solution voids; biotite shows different degrees of decomposition; quartz (yellow, centre) shows internal microfracturing (cross polarized light). Negative No. : SP 93/161/3.



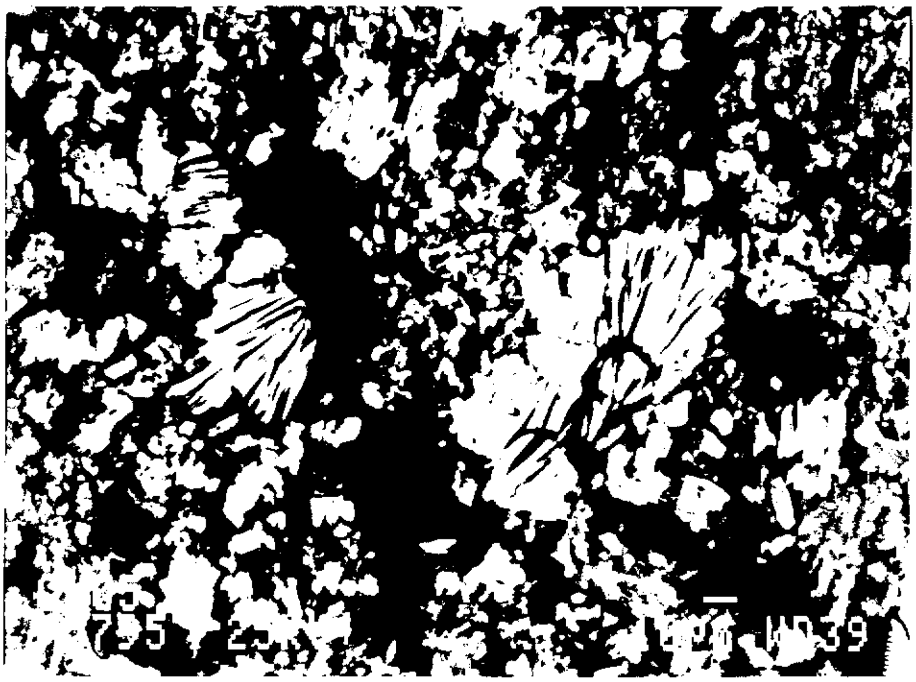

(b) Grain boundaries are open (white); biotite shows some expansion and disturbed structure (Plane polarized light). Negative No. : SP 93/161/4.

Note : Sample SHS5 from Shouson Hill (thin section provided by Dr. Dobereiner). Thin section is slightly thicker than usual.

Plate 15 - Photomicrographs of Highly Decomposed Granite



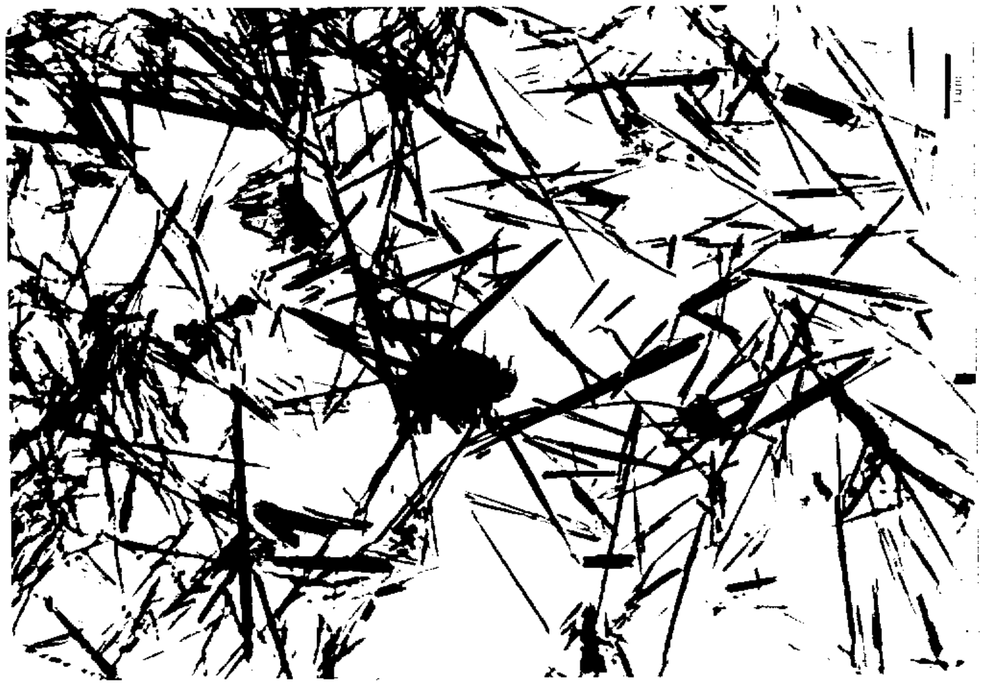
(a) Solution pores and tight microcracks in alkali feldspar. Grain boundary between feldspar and quartz (uniform grey) is partially open (bottom left). Negative No. : SP 93/167/24.



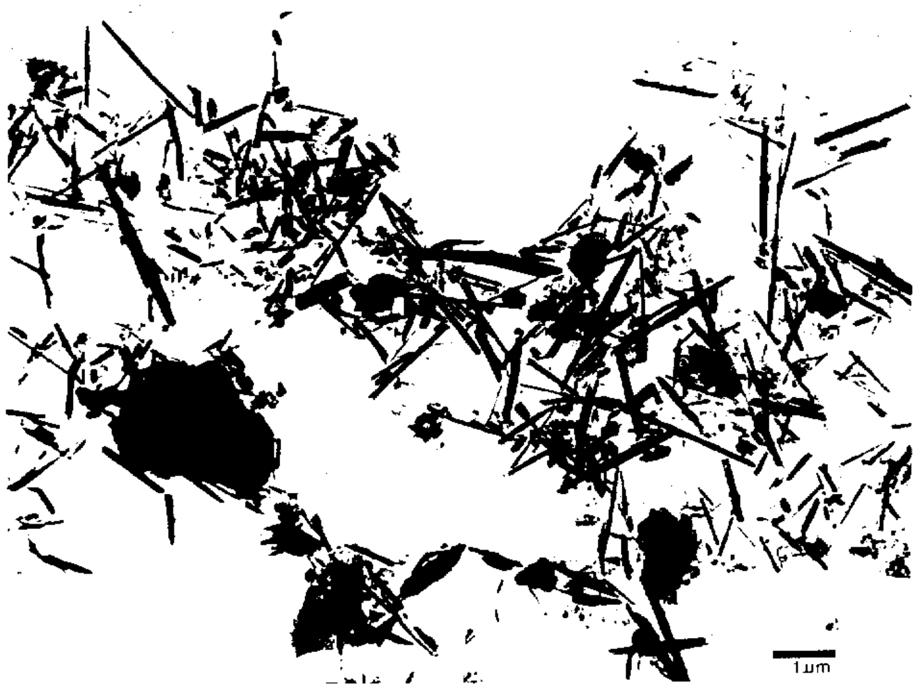

(b) Large kaolinite flakes and other crystalline clay minerals in an amorphous porous clay matrix in completely decomposed plagioclase. Negative No. : SP 93/167/27.

Note : Sample SHS6 from Shouson Hill (photographs provided by Dr. L. Dobereiner).

Plate 16 - SEM Images of Highly Decomposed Granite



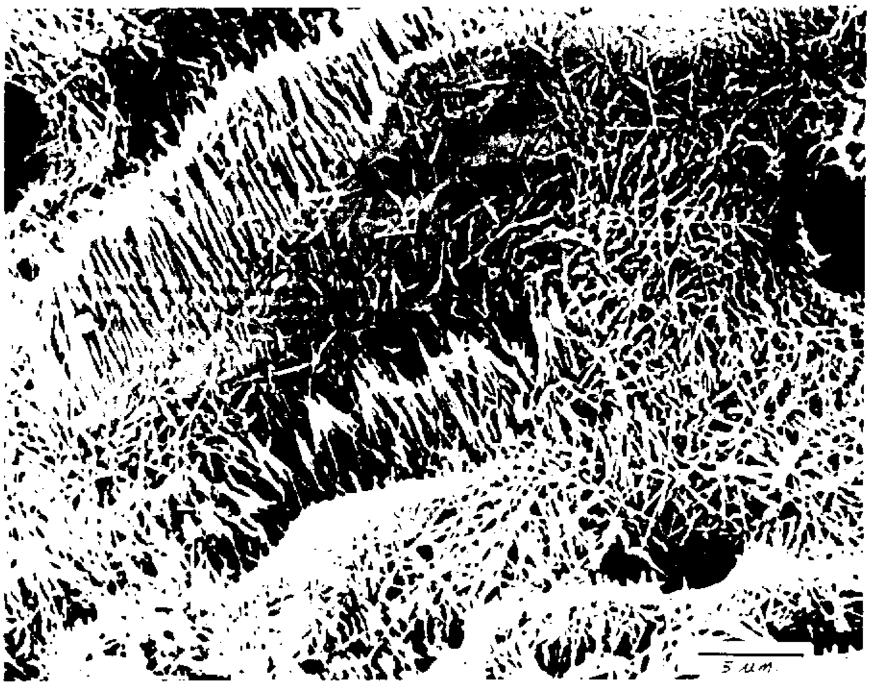
(a) Clay fraction is almost wholly composed of halloysite tubes with occasional platy minerals and iron-oxide aggregations completely decomposed granite sample 404.05 from Shouson Hill. Negative No. : SP 93/167/7.




(b) Higher proportion of platy clay minerals in near surface completely decomposed (disintegrated) granite sample 404.07 from Shouson Hill. Negative No. : SP 93/167/5.

Note : Photographs provided by Dr. Smart and Dr. Awoleye.

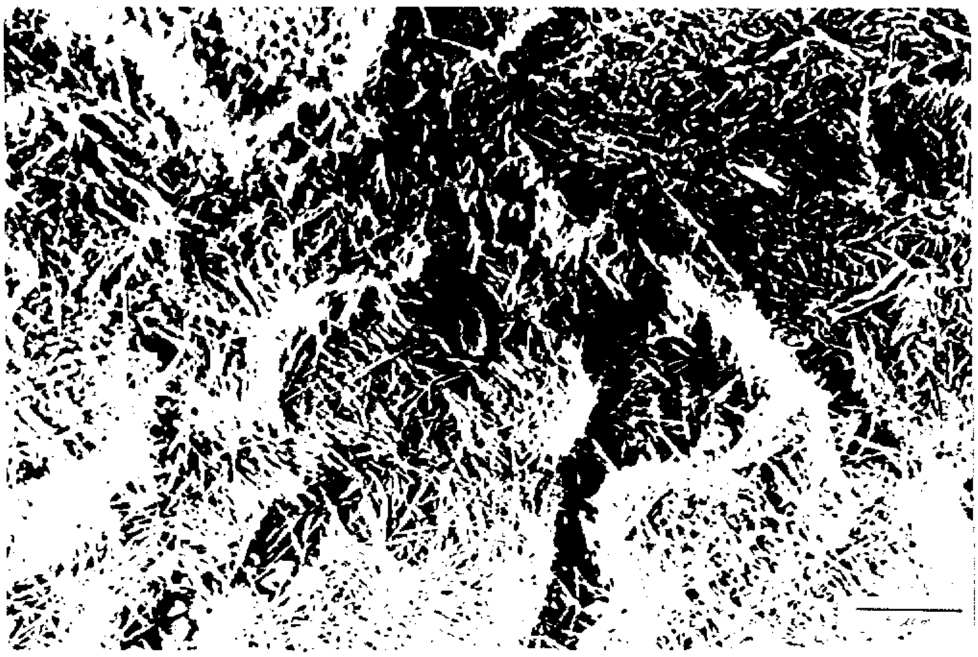
Plate 17 - TEM Micrographs of Dispersed, Completely Decomposed Granite Showing Halloysite Tubes and Some Clay Plates




Long fibres of halloysite being formed from plagioclase (?); Voids have more or less circular cross-section. Negative No. : SP 93/167/3.

Note : Sample 404.05 from Shouson Hill (photograph provided by Dr. Awoleye and Dr. Smart).

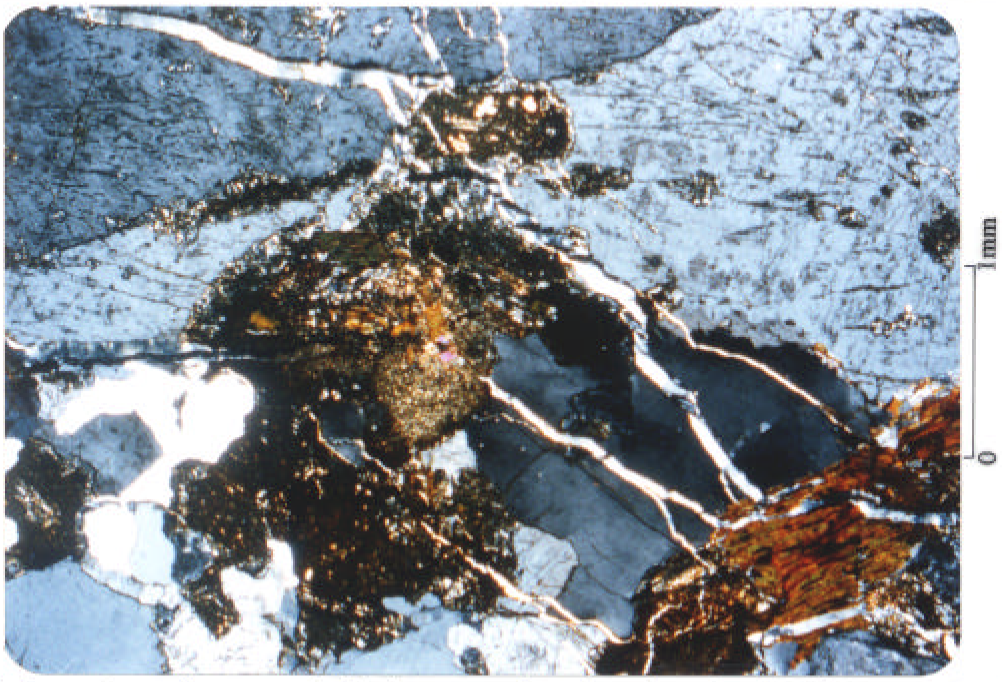
Plate 18 - SEM Micrograph of Halloysite Tubes Growing from Primary Mineral (most probably plagioclase)



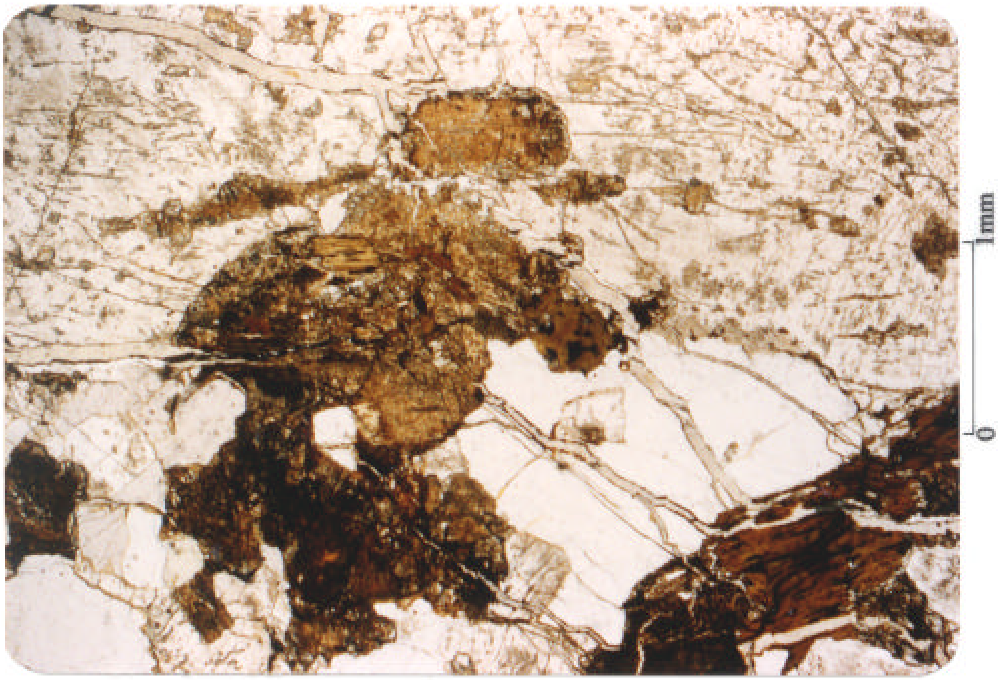
Part of a completely decomposed feldspar grain, completely replaced by fibrous halloysite.
Negative No. : SP 93/167/1

Note : Sample 404.05 from Shouson Hill (photograph provided by Dr. Awoleye and Dr. Smart).

Plate 19 - SEM Micrograph of Completely Decomposed Feldspar



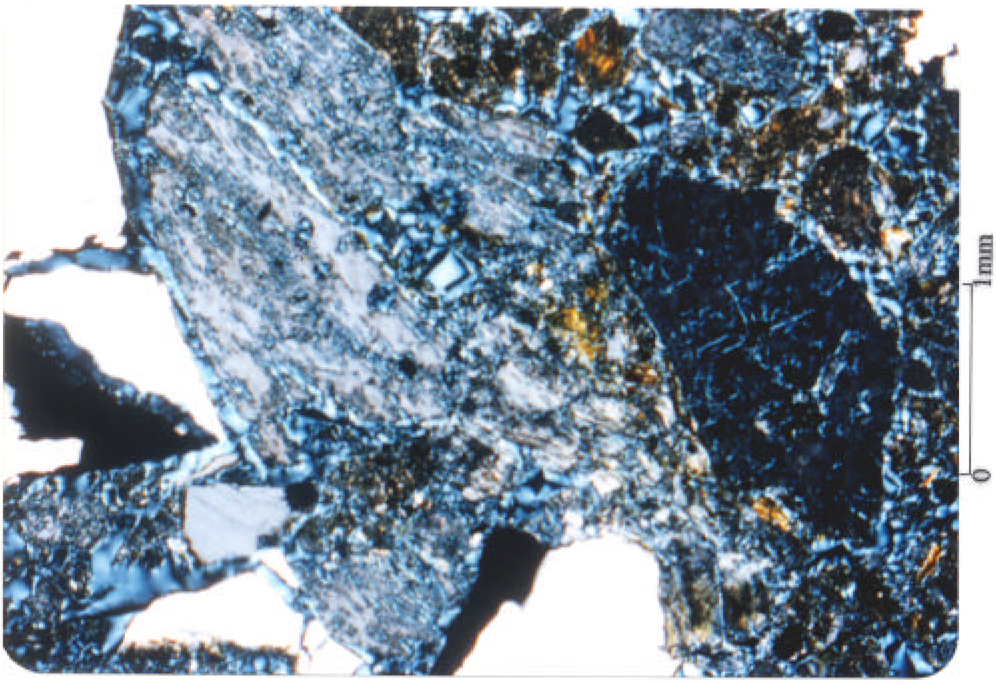

(a) Plagioclases (centre) are completely decomposed to clay minerals; alkali feldspars (top left and right) show void formation by solution and slight decomposition to clay minerals; some grain boundaries are open but some are tightly interlocking. (Cross polarized light). Negative No. : SP 93/160/19.



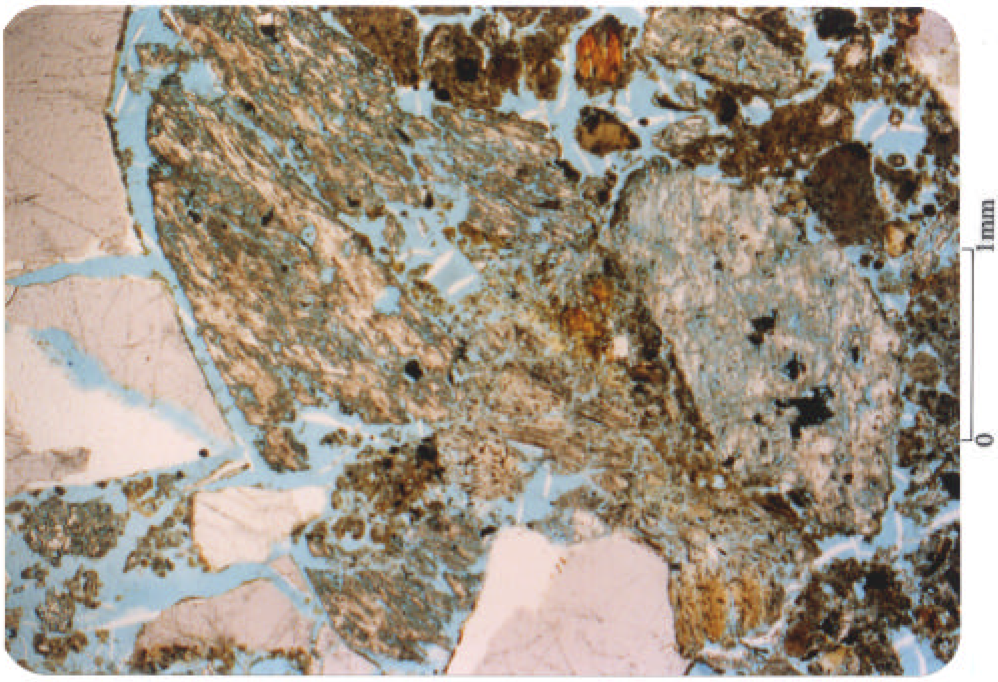

(b) Open microcracks through grains and along some grain boundaries. Solution (?). Channels and holes in alkali feldspar (top right). (Plane polarized light). Negative No. : SP 93/160/20.

Note : Sample 404.05 from Shouson Hill (thin section supplied by Dr. Smart of Glasgow University).

Plate 20 - Photomicrographs of Dense Completely Decomposed Granite



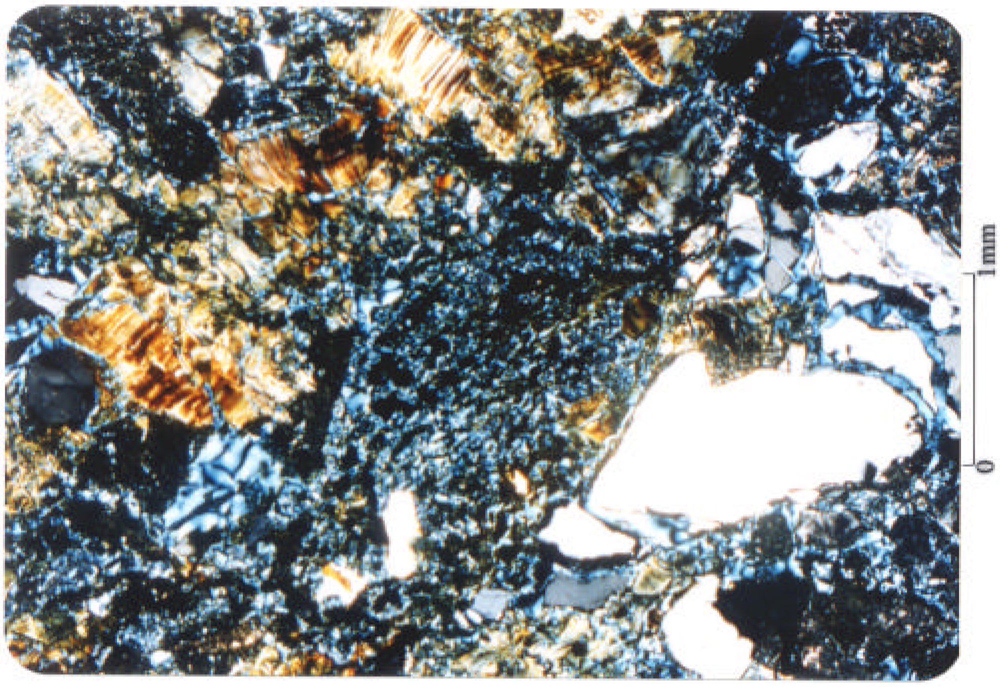

(a) Plagioclase (top right) is completely decomposed with porous microfabric; alkali feldspars (centre) is showing a high degree of void formation by solution (blue areas); almost all grain boundaries are open. (Cross polarized light). Negative No. : SP 93/159/20.



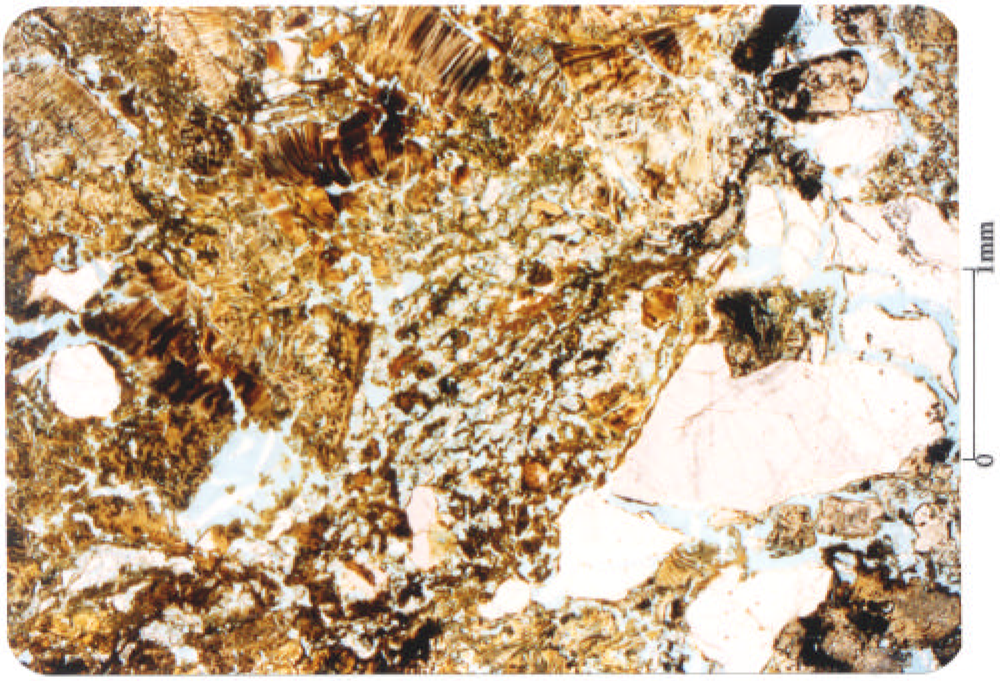

(b) Open porous fabric with honeycombed alkali feldspars, completely decomposed plagioclases and open grain boundaries. (Plane polarized light). Negative No. : SP 93/159/21.

Note : Sample SH8 from Shouson Hill.

Plate 21 - Photomicrographs of Loose Completely Decomposed Granite



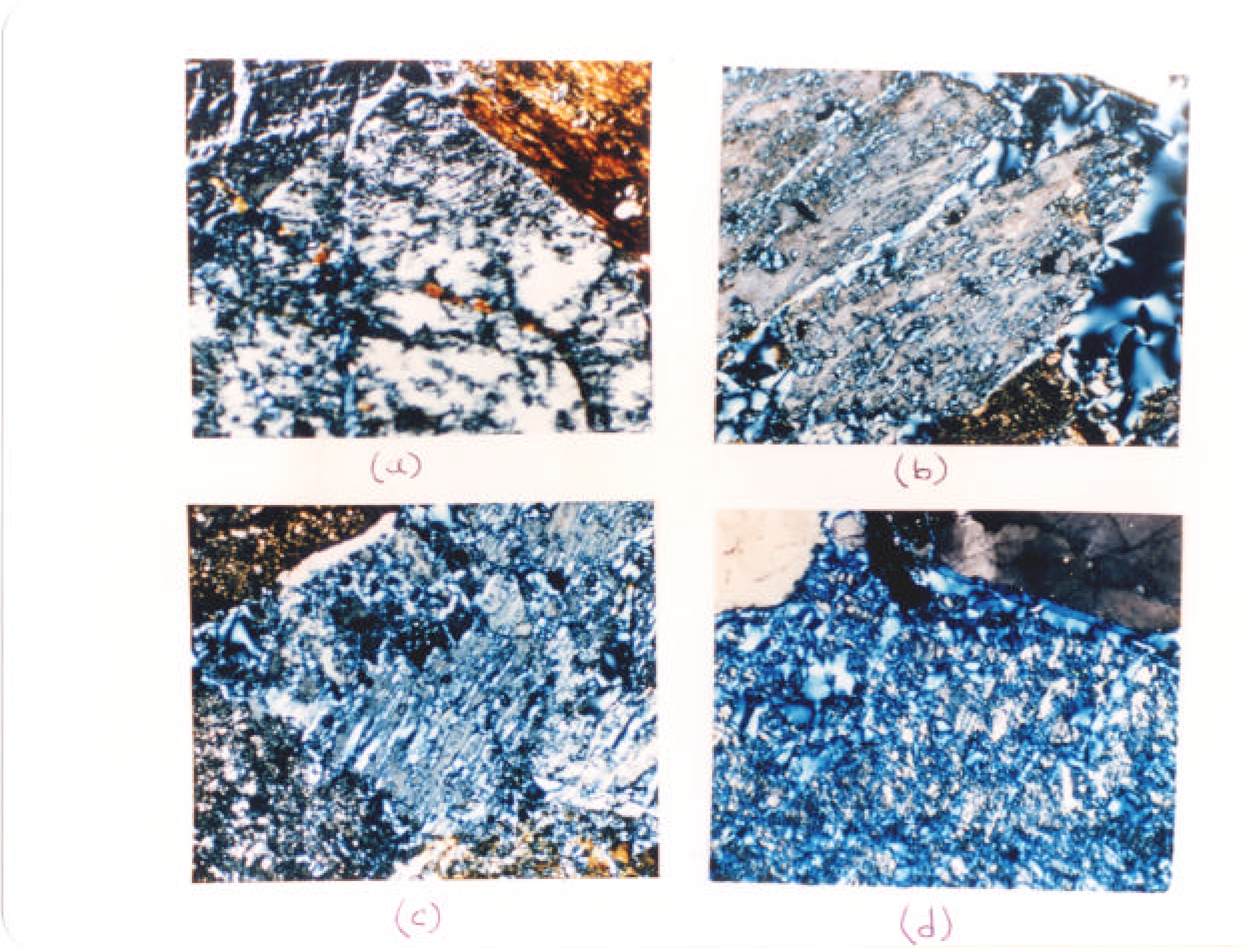

(a) All feldspars are completely decomposed to clay minerals; biotite is completely decomposed to mixture of clay and micaceous minerals and iron-oxides; reduced quartz content. (Cross polarized light). Negative No. : SP 93/159/32.




(b) Partial iron-oxide cementation (brown areas) of decomposed feldspars. Open porous (blue areas) fabric is formed as a result of leaching of clay minerals in well-drained, near-surface conditions. (Plane polarized light). Negative No. : SP 93/159/33.

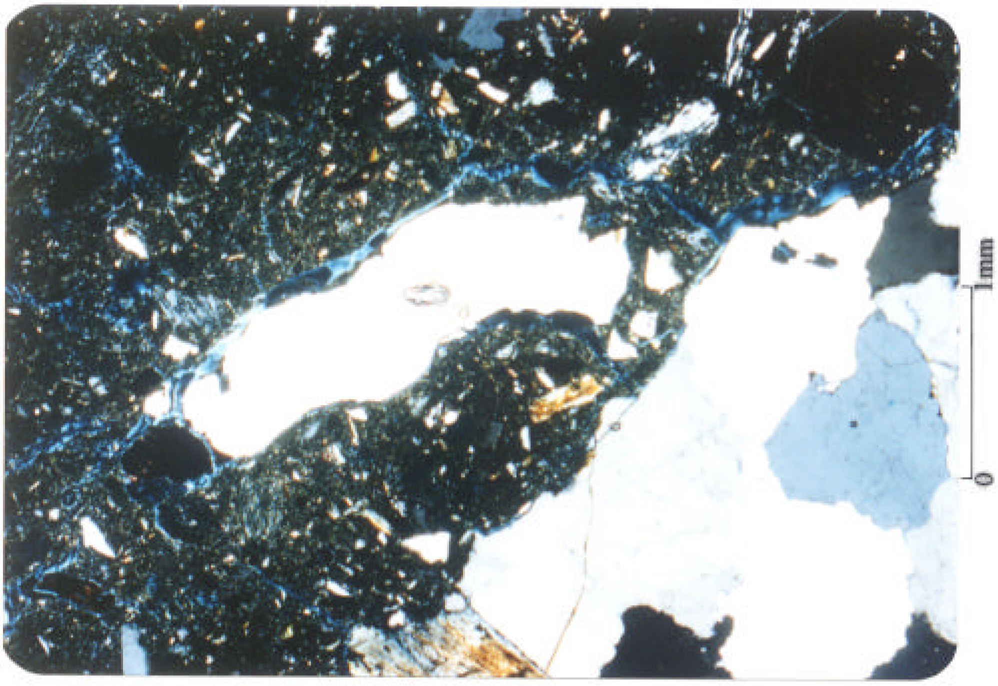
Note : Sample KP1 from King's Park.

Plate 22 - Photomicrographs of Altered Granite

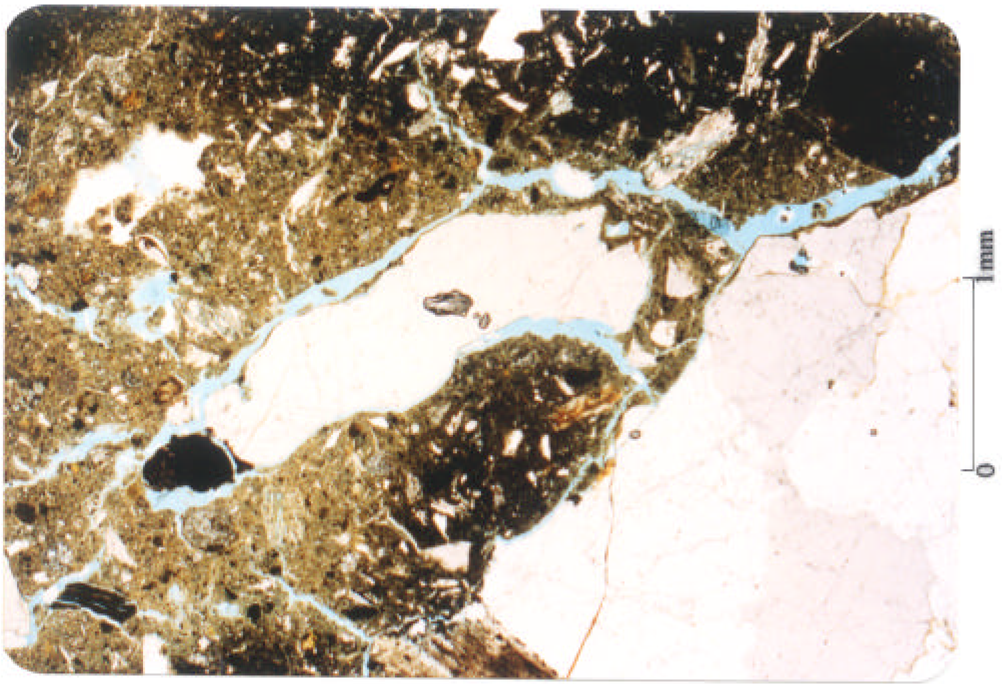



Negative No. : SP 93/214/7A

Plate 23 - Various Stages in the Development of Honeycombed Alkali Feldspars in Completely Decomposed Granite



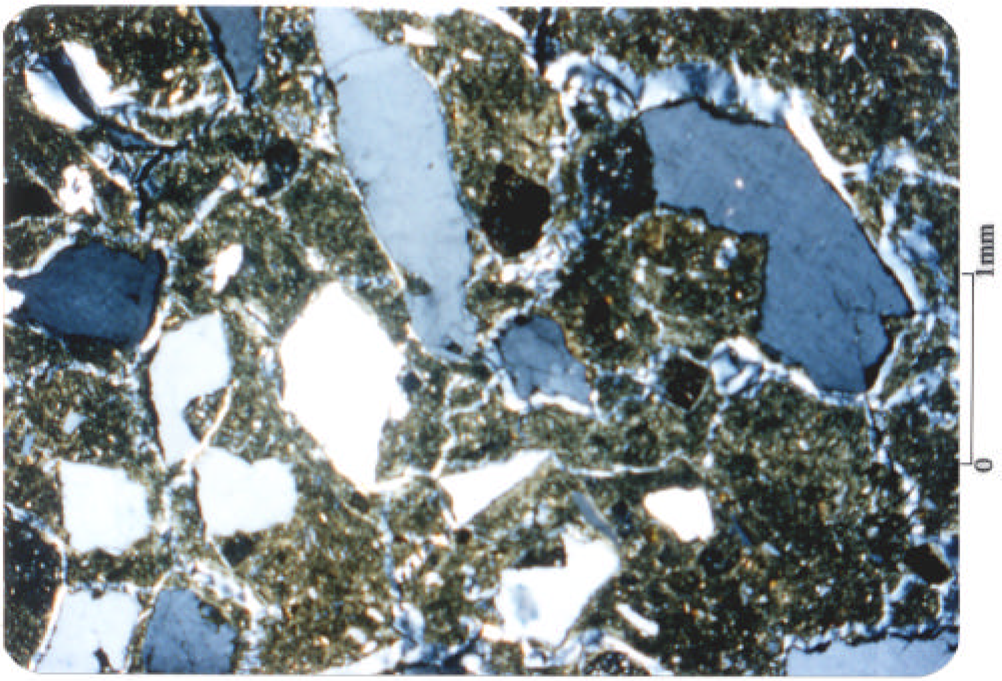

(a) Collapsed fabric (left and top) with fragments of quartz, occasional alkali feldspars and micas in a dense clay mineral matrix, weakly cemented by iron-oxides. (Cross polarized light). Negative No. : SP 93/159/28.



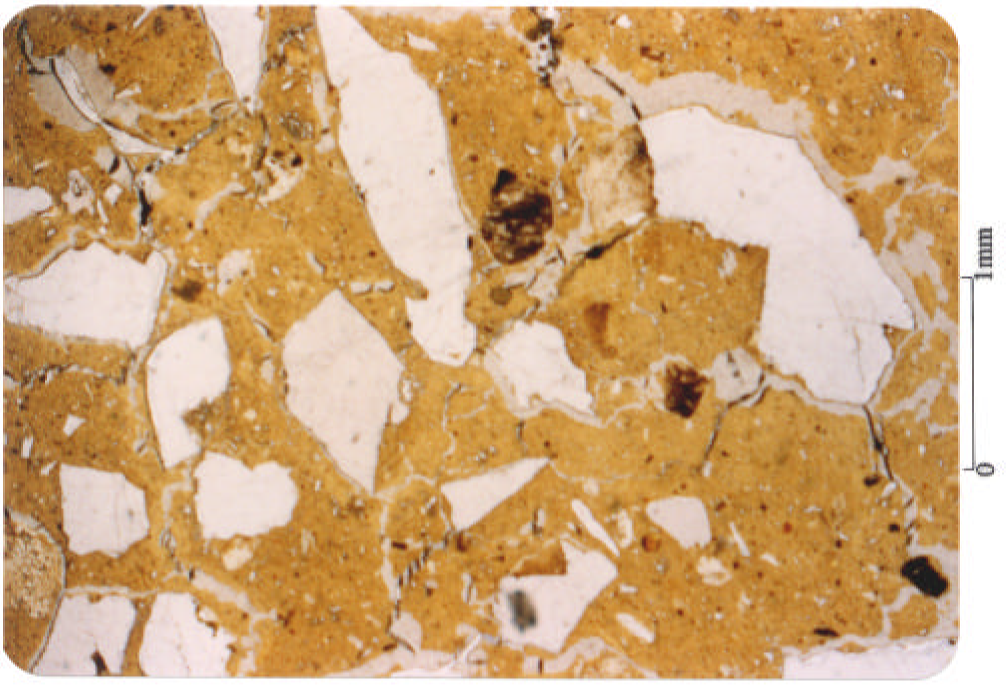

(b) Detail of above in plane polarized light. Negative No. : SP 93/159/29.

Note : Sample SH3 from Shouson Hill.

Plate 24 - Photomicrographs of Transition Soil




(a) Quartz grains, reduced in size, in a dense clay mineral fabric. (Cross polarized light). Negative No. : SP 93/160/21.

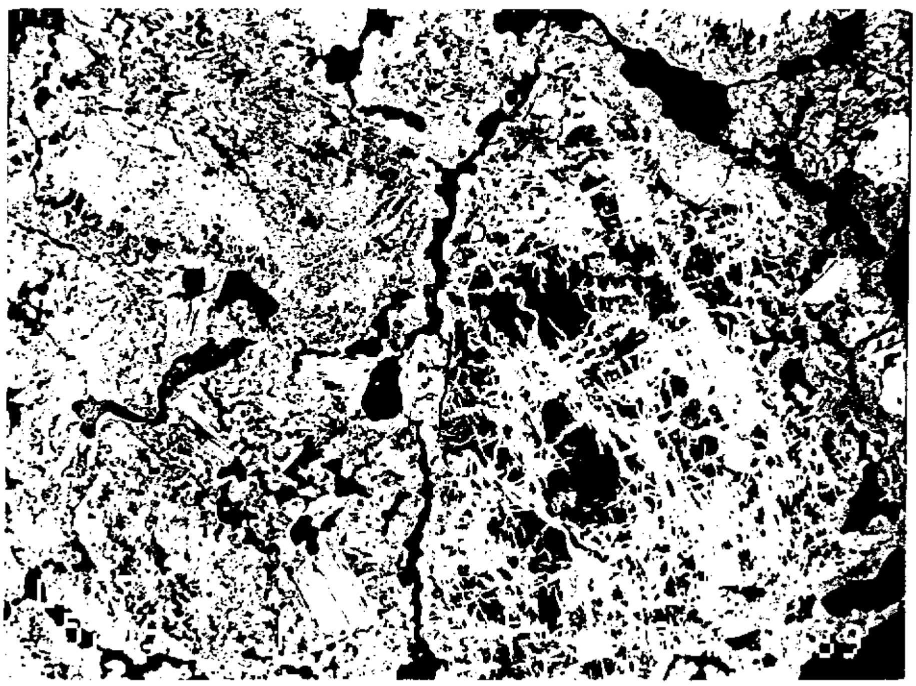



(b) Detail of above in plane polarized light. Negative No. : SP 93/160/22.

Note : Sample 404.08 from Shouson Hill (thin section provided by Dr. Smart).

Plate 25 - Photomicrographs of Residual Soil

(a) Porous (dark grey) clay matrix with silt to sand size quartz grains; occasional mica fragments are present; some areas are rich in iron hydroxides (white). Negative No. : SP 93/167/30.



(b) Another portion of the same specimen showing clay matrix with secondary pores and microcracks; no primary grain outlines are apparent. Negative No. : SP 93/167/33.

Note : Sample SHS1 from Shouson Hill (photographs provided by Dr. L. Dobereiner).

Plate 26 - SEM Images of Residual Soil

# APPENDIX A

# SAMPLE DESCRIPTIONS

## SAMPLE DESCRIPTIONS OF GRANITIC ROCKS

Locality : Shouson Hill, Hong Kong Island

Notes 1. Sample nos assigned by Awoleye (1991), 2. Sample nos assigned by Hencher (1990), 3. Sample nos assigned by Dobeirener, 4. Sample nos assigned by Cheung & Greenway (1987).

| Sample No. | Decomposition Grade | Location | Description of Hand Specimen |
|---|---|---|---|
| (404.01)[1] | 'Fresh' | Sample taken from inside a 4 m diameter corestone in moderately weathered granite zone, approx. 20 m below original ground surface before cutting. | Very strong, light pinkish grey, medium-grained (2 to 6 mm) granite. Equigranular texture with occasional feldspars up to 10 mm in diameter; biotite content < 5%. All constituents are hard and sound, except occasional feldspars showing 'cloudiness' at their centres. |
| (404.02)[1] | Slightly Decomposed | Sample taken from a 0.5 m diameter, slightly decomposed corestone in completely weathered granite zone, within 10 m of the original ground surface before cutting. | The sample consists of a moderately strong, yellowish brown stained rim (3 to 15 mm thick) and an unstained pinkish grey, strong to very strong inner zone. Greenish grey to milky grey discoloration of plagioclases indicates slight decomposition in the 'fresh' core. Some plagioclases are gritty to hard in the stained zone. |

| | | | |
|---|---|---|---|
| (404.03)[1] | Moderately Decomposed | Sample taken from a 0.5 m diameter corestone in completely weathered granite zone, within 10 m of the original ground surface. | Moderately strong, completely discoloured, light yellowish grey. The interior of the sample appears less weathered than the exterior which shows a stronger yellowish brown staining. Plagioclases are generally hard, but occasional grains are slightly gritty. Alkali feldspars are hard, some are microfractured. Biotite is still black and shiny but reddish brown staining is present around many grains indicating slight decomposition. |
| (404.04)[1] | Highly Decomposed (strong end) | Sample taken from a 0.4 m diameter boulder (corestone), recently excavated from the slope, in completely weathered granite zone. | Weak to very weak, yellowish brown, completely discoloured, microfractured throughout with some grain boundaries open. Some plagioclass are hard but most are gritty, occasionally powdery, indicating slight to moderate decomposition. Alkali feldspars are fresh to slightly decomposed, but highly microfractured. Biotite shows some loss of shiny black colour. Some quartz surfaces are dull. |
| (404.05)[1] | Completely Decomposed (Normally decomposed) | Sample taken from slope surface, 2 m below the crest of a cutting in completely weathered granite zone. | Extremely weak, yellowish grey, completely discoloured, completely decomposed granite. Plagioclass are gritty to powdery, alkali feldspars are hard to slightly gritty, but highly microfractured. Biotite is black to greenish grey to silvery grey, softened. Quartz surfaces are dull. Rock fabric is |

| | | | |
|---|---|---|---|
| | | | fractured throughout, most grain boundaries are open. (Gravelly sand with little clay and sand) |
| (404.06)[1] | Completely Decomposed (altered) | Sample taken from slope surface, 2.5 m below the crest of a cutting, adjacent to a quartz kaolin vein. | Extremely weak to very dense, yellowish grey, completely discoloured, completely decomposed and hydrothermally altered (kaolinized). Chemical decomposition is intenser than 404.05, with most plagioclases soft to powdery and most alkali feldspars gritty. Quartz is very dull, reduced in content (less than 30%). (Silty gravelly sand with little clay) |
| (404.07)[1] | Completely Decomposed (disintegrated) | Sample taken from crest of a slope, adjacent to a moderately/highly decomposed corestone in completely weathered granite zone. | Loose, light yellowish grey, completely discoloured, completely disintegrated and decomposed. Plagioclases and alkali feldspars are less decomposed than 404.05, but more microfractured. Granitic fabric is partially lost but due to intense degree of disintegration. (Silty sandy gravel with little clay) |
| (404.08)[1] | Residual Soil | Top of hill, 0.3 m below ground surface, in residual soil zone (1-2 m thick). | Yellowish orange with no apparent granitic fabric. Dull quartz grains ( 30-40%) in a structureless clayey silt material. Large voids (1-2 mm in diameter) and fine roots are present. (Silty sandy clayey fine gravel) |

| | | | |
|---|---|---|---|
| SHS13 (GHG1)[3] | 'Fresh' Granite | Sample taken from inside a 3 m diameter 'fresh' corestone at 15 m depth in moderately weathered granite zone. | Very strong, light pinkish grey, medium-grained (1 to 4 mm) granite. Equigranular texture with occasional grains up to 10 mm. All constituents are hard and sound, except some plagioclases showing 'cloudiness' at their centres. |
| SHS12 (GHG2)[3] (HG2)[2] | Slightly Decomposed | Sample taken from a corestone excavated during road widening, in completely weathered granite zone. | Very strong pinkish grey, fresher core with strong yellowish grey to yellowish brown rim (colour banded), about 50 mm wide. Some plagioclases are slightly gritty and occasional transgranular microcracks are present in the stained rim. |
| SHS11 (GHG3)[3] (HG3)[2] | Moderately Decomposed | Sample taken from a corestone adjacent to a joint showing hydrothermal alteration, about 1 m below ground surface (see Figure 5 and Plate 6). | Strong, light yellowish grey core with moderately strong reddish brown rim, completely discoloured, slightly altered granite. Microfractured particularly in the stained rim. Some plagioclases are gritty particularly in the stained rim. Biotite is black to greenish black, with reddish brown staining around most grains. |
| SHS10 (GHG4)[3] (HG3)[2] | Moderately Decomposed with Highly Decomposed Rim | Sample taken from a corestone, about 2 m below crest of a cutting (see Figure 5). | Weak (rim) to moderately strong (core), light yellowish grey, completely discoloured. |

| | | | |
|---|---|---|---|
| SHS8 (HG4S)[2] | Highly Decomposed (strong end) | Sample taken from a corestone, adjacent to SHS10. | Weak, yellowish grey, completely discoloured, microfractured throughout with generally tight microcracks and some slightly open grain boundaries. Most plagioclases are gritty, occasionally powdery. Some alkali feldspars are slightly gritty (microfractured). Biotite is greenish black. Some quartz surfaces are dull. |
| SHS9 (HG4)[2] | Highly Decomposed (slight effects of hydrothermal alteration) | Block sample taken at 3.2 m depth in a trial pit, about 10 to 12 m below original ground surface before cutting (Figure 5). | Very weak, yellowish grey, highly microfractured with some open grain boundaries. Plagioclases are powdery to gritty, clayey adjacent to kaolin veins and joints. Alkali feldspars are gritty. Biotite is greenish grey to silvery grey with red staining around the grains. (Relict joints are present in the block sample). (Gravelly sand with little silt) |

| | | | |
|---|---|---|---|
| SHS6 (HG4W)[2] (GHG5)[3] | Highly Decomposed (weak end), affected by hydrothermal alteration | Block samples taken at 2.2 m depth in a trial pit (above SHS9), 9 to 11 m below original ground surface before cutting (Figure 5). | Extremely weak, yellowish grey with yellowish brown along relict joints. The block sample contains a series of horizontal partings and occasional patches of kaolinized granite. Most grain boundaries are open. Plagioclases are powdery (clayey in altered areas), some are gritty. Alkali feldspars are gritty, some are hard. Biotite is greenish black to silvery grey. Quartz is dull and microfractured. (Can be disintegrated into individual grains with strong finger pressure). (Silty gravelly sand) |
| SHS5 (HG5D1)[3] (HG5D2)[3] (GHG6)[2] | Completely Decomposed (Dense and very dense) affected by hydrothermal alteration on one side. | Block samples taken at 1.2 m depth in a trial pit (above SHS6), about 8-10 m below original ground surface (Figure 5). | Dense (upper portion, HG5D1) to very dense (lower portion, HG5D2), light yellowish grey and reddish brown. The block sample contains relict joints with thin black silty infill. One side (adjacent to a kaolinized granite area in the trial pit) is more decomposed than other parts. Plagioclases are soft to powdery (i.e. highly to completely decomposed). Alkali feldspars are gritty to hard. Quartz is dull. Biotite is greenish grey to silvery grey. Most grain boundaries are open. (Silty gravelly sand with little clay) |

| | | | |
|---|---|---|---|
| SHS7<br>(HG5L)[3] | Completely Decomposed<br><br>(Loose), possibly affected by hydrothermal alteration along joints, etc. | Block sample taken at 1.2 m depth in a trial pit, a few metres below original ground surface before cutting, adjacent to a kaolinized granite area in the pit. | Loose, yellowish pinkish grey. Small patches showing no granitic fabric (structureless clayey silty sand). Plagioclases are clayey to powdery. Alkali feldspars are powdery, occasionally gritty. Quartz is dull to transparent, fractured. Clay coating to individual grains. Minor roots, up to 2 mm in diameter.<br>(Silty gravelly sand with little clay) |
| SHS1<br>(HG6)[2]<br>(GHG7)[3] | Residual Soil of Granite | Block samples taken at 0.7 m below ground surface. | Dense, yellowish brown, with small patches of granite fabric. Fine gravel and sand size quartz in a clayey silt matrix. No feldspars are visible apart from occasional highly to completely decomposed, soft to powdery alkali feldspar pseudomorphs. Minor roots, and macropores up to 2 mm in diameter.<br>(Clayey gravelly sandy silt) |

Specimens analysed for the study on Direct Shear Testing of a Granitic Soil (Cheung & Greenway 1987; Irfan 1986).

| Sample No. | Decomposition Grade | Location | Description of Hand Specimen |
|---|---|---|---|
| (Unnumbered) | 'Fresh' | Sample taken from inside a partially discoloured corestone in moderately weathered granite zone. | Light pinkish grey with grey, quartz ( 35 to 40%) pink alkali feldspar, milky white plagioclase and black biotite (< 5%). Medium grained with grains at 1 to 5 mm, occasionally at 10 mm. |

| | | | |
|---|---|---|---|
| HS5 | Highly Decomposed | Hand specimen taken from a highly decomposed/disintegrated corestone on newly cut slope surface in completely weathered granite zone | Very weak rock<br><br>(sandy coarse gravel with little silt) |
| HS4 | Completely Decomposed (Disintegrated) | Hand specimen taken adjacent to a highly decomposed corestone, 2-3 m below crest of a newly cut slope. | (sandy gravel with little silt) |
| SH3 | Completely Decomposed (Altered) | Hand speicmen taken from a kaolinized area on the newly cut slope face | Light pink to creamy white. All feldspars are decomposed to soft to powdery pseudomorphs. biotite is colourless (muscovite). Quartz content is reduced to below 20%.<br>(clayey sandy silt) |
| SH8 (TP8)[4] | Completely Decomposed | Block sample taken at a depth of 2.4 m in a trial pit, top of hill | Medium dense, yellowish grey with patches of reddish brown. Plagioclases are soft to powdery. Some alkali feldspars are gritty, most are hard but microfractured. Quartz shows some loss of lustre. Biotite is greenish grey to silvery grey. There is evidence of very slight loss of fabric at places.<br>(Silty sand-gravel with little clay) |
| SH6 (TP6)[4] | Completely Decomposed | Block sample taken at a depth of 2.4 m in a trial pit. | Similar to SH8 with slightly higher biotite content.<br>(silty sand-gravel with little clay) |

| | | | |
|---|---|---|---|
| SH5 (TP5)[4] | Completely Decomposed (affected by hydrothermal alteration) | Block sample taken at a depth of 2.0 m, possibly adjacent to a quartz-kaolin vein. | All plagioclases and alkali feldspars are decomposed to soft clayey pseudomorphs on one side of the block (affected by alteration), but some powdery to gritty feldspars occur on the other side. (gravelly silty sand with little clay) |
| SH7 (TP7)[4] | Completely Decomposed with small fabric loss (transition soil) | Block sample taken at a depth of 1.7 m in a trial pit. | Light yellowish grey, with partial loss of granitic fabric throughout the sample. All feldspars are powdery to soft in areas still retaining fabric. Quartz is dull and fractured. Occasional relict discontinuities are present. (Silty gravelly sand with little clay) |
| SH3 (TP3)[4] | Transition soil with large fabric loss | Block sample taken at a depth of 0.9 m in the transition soil zone. | Light yellowish brown, with large patches of structureless soil. Feldspars are only recognizable in areas retaining granitic fabric, generally as powdery to soft grains. Quartz is dull and shows evidence of solution. There are a number of partings (macrofractures) in the sample with black material coating along some of them (silty gravelly sand with some clay). |

Locality : Kings's Park, Homantin, Kowloon

Note : (5) - Remainder of some block specimens tested by Massey (1979).

| Sample No. | Decomposition Grade | Location | Description of Hand Specimen |
|---|---|---|---|
| KPO1<br>KP02 | 'Fresh' | Samples taken from inside a 4 m diameter corestone on cut slope surface in completely weathered granite zone. | Strong, megacrystic medium-grained granite with feldspar crystals up to 20 mm in a matrix of quartz, feldspars and biotite (1 to 5 mm). Biotite content is higher than other granites, at 10% to 20%. |
| KP1<br>KP2 | Completely Decomposed (Altered) with slight fabric loss | Block samples taken at a depth of? in a trial pit, on side slope below King's Park. | Reddish brown with patches of yellowish grey, completely decomposed (altered) megacrystic granite. Granite fabric is locally destroyed, probably resulting from intense hydrothermal alteration and more recent leaching. Possible slight cementation by iron-oxides. All feldspars are decomposed to powdery to soft pseudomorphs. Biotite is changed to colourless flakes. Quartz is very dull. Pores up to 2 mm in diameter are present. |

Locality : Homantin, Kowloon

| | | | |
|---|---|---|---|
| H1 | Completely Decomposed (very dense with small fabric loss) | Block sample taken from a depth of m. | Dense (exterior) to extremely weak (interior) light yellowish grey with patches of reddish brown, coarse-grained megacrystic granite. There are small patches without granitic fabric particularly on the exterior of the block. Majority of feldspars are decomposed to powdery grains, some are gritty, occasionally hard. Biotite is changed to silvery grey flakes, some with reddish brown coating. Quartz grains (up to 6 mm in size) are fractured. Possible slight effects of hydrothermal alteration (chloritized biotite) (silty gravelly sand). |

# APPENDIX B

## DETAILED MINERALOGY AND FABRIC DESCRIPTIONS

## B. DETAILED MINERALOGICAL AND FABRIC DESCRIPTIONS

### B.1 Fresh Granite

In the fresh rock, all constituents are undecomposed with the exception of plagioclases which may show a small amount of sericitization (i.e. growth of hydrous mica or muscovite). Muscovite with well-developed cleavage may also occur in small amounts replacing alkali feldspar. Biotite may show partial alteration to chlorite. This alteration in the fresh rock is the result of post-magmatic processes (e.g. hydrothermal alteration), as is the sericitization of feldspars. Occasional tight and unstained microcracks may occur in quartz and feldspar grains. Grain boundaries are unstained.

### B.2 Slightly Decomposed Granite

Chemical analysis results (Table 9) show a slight reduction in the weight contents of $Na_2O$ and CaO indicating slight chemical alteration of Ca-Na bearing minerals (i.e. plagioclase). There is also a slight change in the $K_2O$ content, but this difference is not large enough to constitute a significant depletion of the element in the slightly decomposed granite. It could also have occurred from slight variation in the chemical composition of the granite on site. Significant potassium (K) depletion does not occur until very late stages in the completely decomposed grade (Table 11).

There is a gradual change in the petrographical properties as the amount of staining increases in this grade. This is evident in the quantitative micropetrographic analysis results given in Table 12. The amount of alteration of plagioclases increases as the rock becomes more weathered. Almost all grains show micaceous mineral growths, mainly at their central portions and along the twinning and cleavage planes (Plate 11). In the stained rims, the altered areas in the plagioclases are also stained or coated by iron-oxides. There appears to be a change taking place in the type of secondary minerals developing in the plagioclases. It is possible that a small amount of kaolin minerals are formed in addition to muscovite.

### B.3 Moderately Decomposed Granite

Chemical analysis results (Tables 9 and 10) show a slight to noticeable reduction in CaO and $Na_2O$ contents, indicating further progressive decomposition of plagioclases in this grade. Another significant change is the increase in LOI content, which indicates that the clay mineral content is increasing. The $K_2O$ content stays more or less unchanged.

In thin section, the majority of plagioclases show minute micaceous mineral growths. Also, small amounts of less birefringent alteration products are present in some plagioclases together with some minute semi-opaque areas without any obvious clay mineral growth. Some of these may be the locations of dissolution pits and pores observed under the electron microscope (Plate 14). Some of these semi-opaque growths may also represent an intermediate amorphous mineral. Occasional singular pores on plagioclases are large enough to be seen under high magnification of the optical microscope. Kwong (1985) also reported slight to noticeable dissolution of plagioclases in moderately decomposed specimens from a number of granite types in the Territory. The XRD analysis (Table 14) indicates the presence of a small amount of muscovite as the main alteration product. Trace amounts of a kaolin mineral may also be present in the more weathered specimens.

Alkali feldspars are generally unaltered except for the occasional growth of a fine-grained micaceous mineral visible under high magnification. In the more weathered specimens, albite lamellae in perthitic feldspars show slightly increased alteration. There is no apparent evidence of dissolution but most grains contain microcracks, up to 4-5 microcracks per large grain. Some of these microfractures are initiated at the partially decomposed plagioclase inclusions in the alkali feldspars. Biotite shows slight alteration to micaceous minerals, particularly along grain boundaries, and iron-oxide segregation along cleavage planes. Occasional grains show some expansion (exfoliation) of the mica structure resulting from opening of cleavage planes. Some of the microcracks are initiated at the altered biotite grain boundaries.

Modal analyses of the Shouson Hill samples show 6% to 10% altered feldspars and 0.8% to 2.5% altered biotite in this grade (Table 12).

The fabric is moderately microfractured (about 3 to 7 microcracks per 10 mm and up to about 3% of the rock) (Table 12). The microcracks are generally simple branched, tight to slightly open (less than 0.05 mm wide)and mostly iron-oxide stained or infilled. In addition to transgranular microcracks, which go through various minerals, some large alkali feldspars and quartz grains have developed a number of intragranular cracks.

### B.4 Highly Decomposed Granite

Chemical analysis results (Table 9) show a drastic depletion of $Na_2O$ and CaO to almost nil within this grade while the $K_2O$ content shows a noticeable reduction only in the more intensely weathered samples. These results indicate that the plagioclases are being progressively altered to clay minerals with weathering, but the alkali feldspars start altering only at a very late stage in this grade. Correspondingly, the LOI values increase from less than 1% in the moderately decomposed granite to about 4% in the highly decomposed granite (Figure 16). Indicating a significant increase in the OH-bearing clay minerals. Other noticeable increases are in $Al_2O_3$ and total iron-oxide contents.

In thin section, plagioclases are highly to completely decomposed to a cluster of clay minerals with some micaceous minerals still present. The SEM back scatter images of altered plagioclases show the growth of well-crystalline kaolin flakes in a dominantly poorly crystalline to amorphous clay mineral matrix (Plate 16). The XRD traces indicate trace to nil amounts of plagioclase (Figures 6 and 7, Tables 14 and 16) in the more intensely weathered specimens. The modal analysis of Shouson Hill samples shows that the unaltered feldspar content decreases from about 50% in the moderately decomposed rock to less than 30% in this grade (Table 12). While some of the alkali feldspars are almost unaffected by weathering, many are microfractured internally in addition to the transgranular cracks going through the grains. An important aspect of alkali feldspar weathering in this grade is the formation of dissolution features as pits, trenches and channels now visible under the microscope (Plate 16). These features are particularly well-developed in the albitic (plagioclase) lamellae of the perthitic feldspars.

Biotite shows increased decomposition to a mixture of kaolin and micaceous minerals together with some chlorite and iron-oxides. Examination of biotite grains by SEM showed particles from which long fibrous minerals (halloysite) appeared to have been formed. Some of the particles were found to be covered by an unidentified mineral sheet (Awoleye et al, 1989). Some of the partially to completely altered biotite grains also show structural breakdown of the mineral lattice by expansion along the cleavage planes (Plate 16).

Semi-quantitative XRD determinations on bulk specimens indicate a significant increase in the clay mineral content in this grade. This is also confirmed by modal analysis (Table 16). Kaolin minerals form the bulk of the alteration products with some micaceous minerals and trace amounts of chlorite also being present (Tables 14 and 15).

The TEM micrographs of the completely decomposed specimens show long tubes, up to 10 mm, of halloysite (dehydrated form with $7A^{o}$ spacing) as the dominant kaolin mineral with some kaolinite occurring as plates (Plate 17). The SEM images of individual feldspars show halloysite tubes growing directly out of the unaltered parts (Plate 18). Kwong (1985) also identified tubular clay minerals (halloysite?) occurring as clusters radiating from less weathered grain surfaces in various highly decomposed granites in Hong Kong.

The rock fabric is highly microfractured by simple to complex-branched network of tight to open (up to 1 mm wide) transgranular microcracks (Plate 15). Large alkali feldspar and quartz grains show a high degree of internal fracturing. In addition, most alkali feldspars contain dissolution pores and channels. Although the altered plagioclase areas appear to have dense clay microfabrics under the microscope, high resolution electron microscope images indicate numerous minute pores in amongst the clay minerals (Plate 18). Some of the grain boundaries are slightly open.

## B.5 Completely Decomposed Granite

The clay mineralogy and particularly fabric properties vary widely not only between different types but also within the same specimen in the completely decomposed granite grade, as summarised below.

Chemical analysis results indicate the presence of a small amount of Na-bearing minerals (most probably plagioclase) in many of the specimens tested (Tables 10 and 11). The $K_2O$ content, which is a good indicator of the alkali feldspar content in the granites, shows wide variation amongst the various types of completely decomposed granite. In the least weathered (i.e. very dense) or the disintegrated specimens, the $K_2O$ content is similar or slightly reduced in comparison to the highly decomposed granite. In more weathered specimens (i.e. loose), it is reduced significantly which indicates that the K ions are removed from the feldspars either by direct dissolution or via the formation of a clay mineral, which is subsequently removed from the system.

The $SiO_2$ content of the rock contains contribution from all silicates (e.g. quartz, clay minerals, feldspars and mica). The first noticeable reduction in $SiO_2$ content occurs in this grade (Figure 9). However, from the constant volume analysis it is apparent that the $SiO_2$ content shows a gradual but slight reduction in all stages of weathering (Figure 10). This indicates slow removal of silica from the system. Similarly, even though the $Al_2O_3$ content shows an apparent increase in the raw data, its absolute quantity actually decreases gradually with increasing degree of weathering. Very small $K_2O$ contents of the specimens from the megacrystic biotite-rich granite at Kings's Park probably indicate almost complete decomposition of the alkali feldspars. This is confirmed by the optical microscopy and quantitative modal analysis (Table 13). The silica contents are also low, possibly indicating a low amount of quartz in the altered specimens.

In thin section, all plagioclases appear to be completely decomposed to clay minerals, except in the least weathered specimens where a small amount of unaltered feldspar portions is still present (Plates 20 to 23). The microfabrics produced from the decomposition of plagioclases consist of generally dense, tightly packed clay minerals in the sample taken from 11 m depth at Shouson Hill (Plate 20). Near surface specimens (Plate 21) show the development of macropores in the clay microfabrics. This is also the case for the completely decomposed granite sample collected from a small hillside at Homantin. The macropores are generally in the form of holes with rounded edges and longer channels or 'troughs', often going through piles of tubular halloysite as observed under the electron microscope (Plate 18). In hydrothermally altered specimens (Plate 22), the altered plagioclases have denser clay microfabrics. Baynes & Dearman (1978a) reported widely differing clay microfabrics in decomposed feldspars varying from dense, tightly packed aggregates to cardhouse arrangements and porous networks of clay minerals. These reflect variations in the weathering microenvironment producing different amounts and types of decomposition products, combined with a certain amount of eluviation of the smallest particles produced.

Alkali felspars, which are only slightly decomposed but highly microfractured in the highly decomposed grade, are significantly affected by chemical weathering in the completely decomposed granite (Plates 20 to 23).

The alkali feldspar microfabrics developed in the altered specimens are different than those found in the normally weathered specimens. In contrast to the porous non-clay microfabrics in the latter types, alkali feldspars show partial decomposition to clay minerals, particularly in the sodic lamellae. They may be completely decomposed to relatively dense clay microfabrics in more intensely altered specimens. Large flakes of book-like kaolinite with some micaceous minerals are present in some of the altered alkali feldspars from King's Park. Detailed electron microscope study of the altered granite specimens was not undertaken. Therefore, the nature and type of clay minerals formed from alteration of the alkali feldspars are not known in any detail. Halloysite was identified as the dominant clay mineral by electron microscopy in the specimen taken adjacent to a quartz-kaolin vein at Shouson Hill. XRD analyses of more intensely altered specimens from King's Park indicate the presence of significant amounts of kaolinite occurring together with halloysite (Table 15). It is possible that some kaolinite has formed directly from the alteration of alkali feldspars.

Biotite shows almost complete alteration to a variety of secondary products and microfabrics in this grade. In many cases, it is changed into a mixture of hydrous mica, clay minerals and iron-oxides. Chlorite may be present in the altered specimens.

Quartz shows increased microfracturing in this grade. The majority of the microcracks are open, up to 1 mm wide, and many are parallel-sided. In the near-surface specimens, particularly in the disintegrated granite, some of the grains may show intense hairline-type internal cracking. The quartz-feldspar grain contacts show progressive opening with weathering, and in the near surface specimens most grain boundaries are open (Plate 21). Chemical analysis results and the parallel-sided nature of the microcracks indicate a small amount of solution in quartz grains.

Halloysite is the dominant clay mineral with some kaolinite in the completely decomposed granites from Shouson Hill and King's Park, as well as in the sample from Homantin. The study by Kwong (1985) showed that it was also the dominant mineral in various decomposed specimens collected from different granite types in the Territory.

At Shouson Hill site, the XRD analysis of formamide-treated specimens (Figure 8) and the transmission and scanning electron microscopy (Plates 17 and 18) indicated that 7A° halloysite is the main clay mineral with minor kaolinite in the specimens from deeper levels. This was also confirmed by infrared spectroscopy and DSC by Awoleye (1991). Electron microscopy indicated that the main source of halloysite was plagioclase feldspars with some also forming from biotite. With increased weathering, the kaolinite content increases progressively and may form up to 50% of the total clay mineral content in the near-surface specimens (Figure 11). It becomes the dominant clay mineral in the residual soil at Shouson Hill. Small quantities of fine-grained micaceous minerals (most probably 2Ml muscovite or illite) are present in all specimens, with the proportion decreasing progressively upwards in the weathering profile. However, the specimens showing effects of hydrothermal alteration may have significantly higher kaolinite and muscovite contents.

The transmission electron microscopy (Plate 17) showed that the some of the halloysite tubes are up to 9 μm long, with many at 4 to 5 μm, even after the specimens were subjected to ultrasonic dispersion. In the disintegrated specimen taken near the ground surface equal proportions of smaller size halloysite and platy kaolinite (less than 1 μm) wree observed by Awoleye.

The halloysite mineral identified in all XRD traces in this grade is the dehydrated ($2H_2O$) type (or metahalloysite). Hydrated halloysite ($4H_2O$ form with $10^oA$ spacing) was only identified in the altered King's Park specimens. Hydrated halloysite can dehydrate rapidly in room temperature and low humidities (Hughes, 1966). All specimens were air-dried prior to the XRD analysis in this study. Air drying combined with long time delay between collection of the specimens and testing by the overseas laboratories might have turned all hydrated halloysite into the dehydrated form.

Iron-oxide minerals. Electron microscopy by Awoleye (1991) revealed the presence of small quantities of poorly crystalline ferrihydrite, rather than hematite, in the red mottles of the least weathered Shouson Hill specimens in this grade. Minute quantities of ferrihydrite was also present in the acid ammonium oxalate extracts of more weathered specimens. Goethite was the dominant iron mineral in all the specimens. The occurrence of goethite in the specimens, up to 3% of the total soil, was expected due to their yellowish colour.

No detailed study was undertaken on the nature of iron minerals in the King's Park specimens. Very reddish brown colour of the soil specimens indicate that hematite may also be present. Optical microscopy indicated the presence of magnetite, usually in association with biotite, in the fresh granite. Alteration of magnetite by oxidation produces hematite (Gilkes & Suddhiprakaran, 1979).

Fabric. In general, the granitic fabric is still present but intensely microfractured by a network of complex branched, parallel-sided transgranular and intragranular microcracks. Most grain boundaries are open. Degree of fracturing is higher in more intensely decomposed and in particular, the disintegrated specimens.

The soil fabric in this grade is composed of a heterogeneous mixture of microfractured, sand size, strong quartz and porous to very porous weak honeycombed alkali feldspar grains, together with porous to dense aggregations of clay minerals. The clay minerals and unaltered grains are coated and locally weakly cemented by goethite. Hematite may also occur as the cementing material, particularly in soils formed from the rocks containing magnetite. The grain contacts between the feldspars and quartz are mostly open but clay mineral and iron-oxide bridges may exist across the contacts (Collins, 1985a). Significant variations in fabric can occur not only between block samples taken side by side but also within each soil specimen in the completely decomposed grade.

In addition to the fabric variations at micro-scale, the weathered granite, en masse, may show larger scale macrofabric changes at each site. These may arise from variations in the original rock mineralogy and structure as well as the type and intensity of weathering and pre-weathering processes, the tectonism and the leaching conditions prevailing at each site.

## B.6 Transition Soil

Chemical analysis results show that the $K_2O$ content is further reduced in this grade, particularly in the near surface specimen showing an advanced stage of fabric collapse (Table 11). This indicates further decomposition of alkali feldspars and removal of $K^+$ ions (or clay minerals) from the system.

There is an increase in the degree of chemical alteration of alkali feldspars to clay minerals, as observed in thin section, in contrast to the solution type weathering seen at earlier stages. Occasional fragments of feldspars are present in the fabricless areas. These are probably the remnants of the honeycombed feldspars which have undergone collapse as a result of further weathering and repeated wetting and drying near the ground surface. Granitic fabric is more preserved in the quartz-rich areas than the feldspar-rich areas (Plate 24). Modal analysis shows that the unaltered feldspar content is reduced significantly to about 2.7% of the total soil (about 2.3% excluding microcracks and pores) in the specimens with a large fabric loss (Table 12). Quantitative mineral contents calculated from the results of chemical analysis also gave a similar result, about 3.5% (Table 16).

Plagioclases are completely decomposed to an aggregate of clay minerals. Biotite is further decomposed to a mixture of micaceous and clay minerals. Quartz is extensively microfractured and is broken into small individual fragments in this grade.

Detailed electron microscope studies were not carried out on the transition soil specimens. Therefore, the type and nature of the clay mineral transformations and the microfabrics developed in individual decomposing grains are not known. However, they are expected to be a continuation of the trends seen in the earlier stages of weathering. The XRD analysis indicates that kaolinite is the dominant kaolin mineral, occurring together with some halloysite, particularly in the specimens showing large fabric losses (Table 15). The total kaolin mineral content is also increased in comparison to the completely decomposed specimens, possibly indicating the contribution from the decomposing alkali feldspars. There is a reduction in the secondary mica content. The main iron-oxide mineral is goethite. A small amount of gibbsite, which was detected in residual soil specimens, may also be present in this grade.

In brief, quartz is still the dominant mineral composing almost half of the soil by weight followed by kaolinite and halloysite. The remaining constituents occurring in very small amounts (less than 5%) are unaltered alkali feldspars, muscovite/illite, goethite and a trace amount of chlorite. In addition, the transition soil contains pores and microcracks decreasing in amount upwards in the weathering profile as the fabric is progressively destroyed.

The soil fabric is very variable within very short distances due to the presence of collapsed-fabric areas which increase in proportion upwards in the profile (Plate 24). In general, it consists of a heterogeneous mixture of platy clay minerals (kaolinite) with some tubular halloysite and some silt to sand size unweathered mineral fragments (in collapsed fabric areas), and porous to microfractured clay-sand fabrics similar to those present in the completely decomposed granite.

## B.7 Residual Soil

Chemical analysis results show further reduction of the $K_2O$ content to well below 1.0% in this grade. This indicates almost complete decomposition of alkali feldspars. There is an apparent increase in the $SiO_2$ and $Al_2O_3$ contents of the residual soil specimens in comparison to the transition soil. The increase in the $SiO_2$ content probably reflects the increased quartz content in the soil resulting from the removal of clay minerals by eluviation near the ground surface. The presence of a minor amount of aluminium-bearing gibbsite may also be contributing to the higher Al content of the soil.

In thin section, decomposed plagioclase pseudomorphs are largely broken up and the grain outlines are no longer visible (Plates 25 and 26). Occasional small unaltered or honeycombed portions are present in the decomposed alkali feldspar grains, which on occasions retain their crystal outlines. Biotite is completely replaced by clay minerals and usually it is broken up into small fragments. Quartz is largely broken up into small fragments, with some of the larger grains showing intense hairline cracking.

Scanning and transmission electron microscope examinations of the residual soil specimens show a continuation of the halloysite to kaolinite transformation trend seen in the completely decomposed granite, with kaolinite becoming more dominant. The sizes of the clay particles are also reduced, with most of the kaolinite plates and the length of halloysite tubes being less than 1 μm in size. The majority of kaolinite is probably produced from the breakdown and opening (unrolling) of halloysite tubes. There is evidence from optical microscopy that some kaolinite may also be produced directly from the decomposition of alkali feldspars and a small amount from biotite. Hydrothermal alteration, which appears to have taken place at some sites in granitic rocks, is also a possible source for kaolinite. A small reflection at 4.85 A$^{o}$ in the XRD traces and infrared spectroscopy revealed the presence of a small amount of gibbsite in the soil.

The transmission electron microscopy revealed that the iron-oxide minerals occur as aggregations with sizes varying between 1 μm and 3 μm in the residual soil specimens from Shouson Hill. This was also the case with the less decomposed soil specimens discussed previously. Goethite was identified as the only iron-oxide mineral present in the soil. X-ray diffraction of NaOH and HF-treated concentrates of iron-oxides gave sharp goethite peaks at 4.18, 2.69 and 2.45 A° (Awoleye, 1991). The increased sharpness of the peaks suggests an increase in crystallinity of the goethite particles in the residual soil. Also, the goethite particles have a more platy morphology in comparison to the lath-like forms present in the less decomposed granite.

The decomposed granitic fabric is completely destroyed, particularly in the near surface specimens (Plate 25). The soil consists of silt to sand size quartz and occasional alkali feldspar fragments in a very fine-grained clay mineral matrix of mostly platy kaolinite with some tubular halloysite. Small amounts of muscovite/illite and gibbsite may also be present. Although residual soil is generally denser than the saprolitic and transition soils, numerous pores and occasional microcracks are present in the clay matrix. Goethite occurs throughout the matrix as strong aggregations and may locally cement the clay and other soil particles together. There is some evidence of iron-oxide minerals attaching to the edge and surface of clay particles indicating the interaction of the two types of minerals.