MINERALOGICAL AND FABRIC CHARACTERIZATION AND CLASSIFICATION OF WEATHERED VOLCANIC ROCKS IN HONG KONG

GEO REPORT No. 66

T.Y. Irfan

GEOTECHNICAL ENGINEERING OFFICE

CIVIL ENGINEERING DEPARTMENT

THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION

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PREFACE

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R.K.S. Chan
Principal Government Geotechnical Engineer
July 1998

FOREWORD

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.

The results of the research on weathered granitic rocks have already been published in a GEO Report by Irfan (1996a). This document summarizes the study results on the mineralogical and fabric properties of the weathered volcanic rocks, in particular, the tuffs.

The results of the studies on weathered granitic and volcanic rocks have already been used by the GEO in drafting local standards for soil classification and index tests based on BS1377:1990 version (see Chen, 1993). The results of the study on the rock grades are being incorporated into local standards for rock tests being prepared by the GEO.

The report has been written by Dr T. Y. Irfan who also initiated the study, conducted the research and carried out most of the in-house mineralogical and fabric analyses, and coordinated and arranged for testing at overseas institutions and laboratories. The chemical and X-ray diffraction analyses were carried out by the British Geological Survey and at three commercial laboratories in Australia.

Dr S.D.G. Campbell and Dr R. J. Sewell reviewed the draft document.

JB Massey

(J. B. Massey)
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ABSTRACT

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.

The results of the research on weathered granitic rocks have already been described by Irfan (1996a). This document summarizes the study results on the weathered volcanic rocks, in particular, the tuffs. It documents the typical chemical, mineralogical and fabric changes that occur in these rocks due to weathering and other alteration effects.

Based on the results of the study, a model for weathering of volcanic rocks is established. The effects of hydrothermal alteration which are a major influence in profile development and soil formation in Hong Kong are also considered. Modification, similar to those recently proposed for granites (Irfan 1996a), are proposed to the material and mass weathering schemes commonly adopted in Hong Kong for the characterization of volcanic works in engineering uses.

The results of the studies on weathered granitic and volcanic rocks have already been used by the GEO in drafting local standards for soil classification and index tests.

CONTENTS

1. INTRODUCTION

As part of its research and development programme, the Geotechnical Engineering Office has been looking into ways of determining and characterizing 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.

A number of chemical, petrographical and other methods have been used to document and quantify the mineralogy and fabric properties of weathered igneous rocks, in particular the granites, and volcanic rocks at each grade of weathering. These included chemical analyses, X-ray diffraction (XRD) analysis, optical microscopy, scanning and electron microscopy (SEM, TEM) and differential scanning calorimetry.

The results of the study on the weathered granitic rocks have been described by Irfan (1996a, b). This document presents the results of the study on the weathered volcanic rocks. It documents the typical chemical, mineralogical and fabric changes that occur in volcanic rocks due to weathering and other alteration effects, in particularly the tuffs which are widespread in Hong Kong.

The index and engineering properties of weathered volcanic rocks are not discussed here. A review of the mineralogy and structure of saprolitic and residual soils of volcanic and granitic rock origin is given in Irfan (1996b, c), who also discusses the effects of specific mineralogy and structure developed in these materials on the classification and index properties and behaviour.

2. GEOLOGICAL SETTING OF VOLCANIC ROCKS IN HONG KONG

2.1 General

Granites, granodiorites and the associated volcanic rock suite of Mesozoic age underlie a greater part of the Territory of Hong Kong (Figure 1). The volcanic rocks of Jurassic to Cretaceous age, several thousand metres thick, have been intruded by a number of granitic plutons of slightly younger age.

The volcanic rocks, recently grouped by the Hong Kong Geological Survey under the younger Repulse Bay and the older Tsuen Wan volcanic groups, comprise a series of lithostratigraphic formations, each with its own distinctive geological characteristics (see for example, Langford et al. 1995). The volcanic rocks consist mainly of tuffs of pyroclastic origin derived from ash fall and ash flow deposits with some lavas and intercalated sedimentary horizons. The rocks are generally rhyolitic (acidic) in composition with some andesitic rocks occurring locally. Macroscopic features such as flow-banding, flow-folding, auto-brecciation and columnar jointing are present in the lavas as well as in the tuffs. The recent classification of pyroclastic rocks has been in terms of grain size and physical components (Figure 2). Fine ash vitric tuffs and coarse ash crystal tuffs are the dominant rock types occurring in most formations. Other lithologies including tuff breccia, lapilli tuff, andesitic lavas and tuffites (tuffaceous sedimentary rocks), also occur as mappable units. More detailed information on the mineralogy and textural features of the common volcanic rock types is given in Section 9 and in the Geological Survey Memoirs published by GEO.

2.2 Late-Stage Alteration and Metamorphism

Volcanic rocks show local evidence of contact metamorphism close to granitic plutons. The effect of metamorphism is most intense within a few metres of the contacts, resulting in destruction and recrystallization of the original tuff texture and formation of hornblende-to pyroxene-hornfels. However, in most cases, the volcanic rocks near granite contacts are hardly affected. In the Lo Wu-Tuen Mun area, the regional low to medium-grade meta-orphism associated with overthrusting of Palaeozoic basement onto Jurassic volcanic rocks also affected the volcanic rocks resulting in mylonitization and formation of a schistosity in the rocks (Langford et al, 1989). Volcanic rocks also show effects of metasomatic and thermal alteration (hydrothermal alteration) particularly in the vicinity of granitic plutons.

2.3 Structure

The granites and volcanic rocks are affected by faulting dating back to the Mesozoic, the faults being rejuvenated during each subsequent orogeny. The most dominant and persistent fault directions in the Territory are ENE-WSW and the most regionally extensive structures trend NE-SW and NW-SE.

Some large-scale gentle and open folding has been recognised in volcanic rocks overlying granitic plutons (Strange et al, 1990). These are at least in part related to the rise of the underlying granitic plutons into a relatively competent volcanic cover. Two major collapsed caldera-type structures have been postulated in the Sai Kung area (Strange et al, 1990), and a further caldera on Lantau (Langford et al, 1995), which resulted in roughly horizontal or gently dipping volcanic strata at the centres.

Some of the joint sets in the volcanic rocks are clearly related to those formed in granites. Additional joints sets are also developed in volcanic rocks related to folding and faulting due to the intrusion of granites, metamorphism, and the cooling and erosional history. Strong foliation or schistosity is also present in some of the volcanic rocks, in particular in the Northwest New Territories, associated with overthrusting. The stress-release related gently dipping joints are generally poorly developed or non-existent in volcanic rocks. The joint spacing is usually much closer than in the granitic rocks, except perhaps in some crystal tuffs, being generally between 0.1 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 closer in the vicinity of faults and fault zones.

3. WEATHERING PROFILE DEVELOPMENT AND ENGINEERING CLASSIFICATION OF WEATHERED VOLCANIC ROCKS

3.1 Weathering Profile in Volcanic Rocks

The majority of studies on rock weathering and profile descriptions have been confined to the granitoid rocks in Hong Kong. The volcanic rocks have received less attention and only brief references have been made to profile development in these rocks (Powell & Irfan, 1987; Irfan et al, 1987; GCO, 1988; Irfan, 1994). Recently, Irfan (1996a, b) reviewed the common weathering processes responsible for deep weathering profiles which have developed over the igneous and volcanic rocks in Hong Kong.

In general, soil zones of the weathering profile are comparatively shallow in volcanic rocks, usually less than 15 m thick, in contrast to the deep profiles that occur over the granitoid rocks. However, thick soil profiles of up to 35 m have also developed, particularly in the coarser grained volcanic rocks (Figure 3). Deeper soil profiles have been recorded, but these are considered to be confined to faults and closely fractured zones. Corestone development, which is characteristic of the medium- and coarse-grained granites, is not common in weathering profiles developed over volcanic rocks, except in coarse ash tuffs and lapilli tuffs (Plates 1 and 2).

Cataclasis and shearing of the rocks by tectonic processes and granite intrusions and the associated hydrothermal alteration are a major influence in profile development and soil formation at many locations in Hong Kong. Hydrothermal alteration generally results in weakening of rocks and deeper penetration of weathering (Irfan, 1996a; Irfan & Woods, 1997). Some volcanic rocks are more resistant to weathering (e.g. lavas) than others, resulting in well-defined escarpments where resistant rocks cap and protect the softer more easily weathered tuffs. For example, in the western New Territories, the slightly metamorphosed tuffs form thin weathering profiles with corestones, but strongly metamorphosed tuffs generally form resistant ridges (Langford et al, 1990).

The general weathering profile in lithologically uniform volcanic rocks is similar to that of granitoid rocks, and consists of four major layers grading from residual soil at the top to fresh rock at depth. In many localities in Hong Kong, the transitional rock and soil zone is usually relatively thin, except in coarse-grained volcanic rocks which have a similar profile development to medium to coarse-grained granites (Plate 1). In bedded sequences of varying lithology, the rock mass may consist of relatively unweathered bands or beds alternating with decomposed bands or beds. In some cases, the soil layer may be underlain by the fresh rock, with intermediate layers not present (Plate 3).

The residual soil layer over the volcanic rocks is not very well developed, as is the case with granites also. It is generally underlain by the transitional soil layer containing relict rock fabric but no structures. This zone is up to 3 m thick at many locations even on gently to moderately sloping ground.

3.2 Weathering Grade Classification

3.2.1 Classification of Weathered Rock Mass

As the weathering profiles developed over the volcanic rocks are similar to those of the granitic rocks, the same weathering grade classification scheme is generally applicable to both rock types. The six-fold mass grading scheme recommended by BS 5930 (BSI, 1981) has also found favour for classifying various components of the weathering profile developed over volcanic rocks (Powell & Irfan, 1987; GCO, 1990; Irfan, 1994) (see Table 1). The zonal scheme proposed by GCO (1988) is particularly suitable for corestone-forming, generally coarse-grained volcanic rocks (e.g. coarse ash tuffs). However, it is less well suited for fine-grained rocks which show gradual loss of strength with weathering without forming any significant soil material.

The schemes proposed by GCO (1988) and BSI (1981) and the most recent classification schemes proposed by the Geological Society of London (1995) fail to cater adequately in characterizing soil zones of the weathering profile for engineering purposes. A classification scheme for soils formed from weathered rocks in tropical areas has been proposed by the Geological Society of London (1990). However, this scheme is complex and uses many terms unfamiliar to geotechnical engineers. Also, it does not account for the structural characteristics of saprolitic and residual soil layers, that are incorporated in the simpler classification scheme proposed by Wesley & Irfan (1996). A brief description of this scheme together with a critique of various mass weathering classification schemes applicable to rocks in Hong Kong is given in Irfan (1996b).

3.2.2 Classification of Weathered Rock Material

Traditionally, a six-fold decomposition grade scheme has been used in Hong Kong to classify the weathered state of rock material (GCO, 1988). This scheme is generally applicable to most volcanic rocks. Various authors have suggested general characteristics based on observation or simple tests for assessment of decomposition grades, in particular in granitic and volcanic rocks (Hencher & Martin, 1982; GCO, 1988; Irfan, 1988, 1996b).

The most accurate method of describing the degree of decomposition, or weathering in general, is to use a quantitative index. Assessment of decomposition grade should be supplemented by description of the state of disintegration of the rock material as disintegration is also an intrinsic component of weathering. The terms used for description of decomposition grades of rock material may be used for hydrothermally altered rocks also as decomposition is a general term used for chemical changes.

Irfan (1996b) subdivided the 'completely decomposed' granite grade into; (i) completely decomposed, (ii) (completely) disintegrated, and (iii) (completely) altered, based on the dominant type of weathering and alteration process. He also proposed the term 'transition soil' for material that shows partial loss of fabric before it transforms into true residual soil. These subgrades also appear to apply to volcanic rocks. Further division of each subgrade can be made, as necessary, based on relative strength (density or consistency) of the soil material, which is a function of its degree of weathering and alteration.

4. METHODS OF CHARACTERIZATION OF WEATHERED AND ALTERED ROCKS AND THE WEATHERING INDICES

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

Irfan (1996a, b) reviewed the various weathering indices proposed to date and their suitability for granitic rocks in Hong Kong. The suitability of selective weathering indices for volcanic rocks is discussed in Section 10.

5. PREVIOUS WORK ON HONG KONG WEATHERED VOLCANIC ROCKS

Little published data exist on the clay mineralogy and fabric properties of weathered volcanic rocks in Hong Kong, and these are confined to only a few samples collected from a limited number of rock types (Brock, 1943; Parham, 1969; Lumb & Lee, 1975). There is also little mineralogical and chemical data from other countries on the weathering aspects of older volcanic rocks. In order to understand the laboratory and field behaviour of weathered rocks, in particular the soil grades, the basic mineralogical and fabric properties of these rocks and soils need to be characterized. However, characterising these properties for engineering purposes is not easy because of their great variability and inhomogeneity, particularly in the case of volcanic rocks, as a result of their geological and weathering history.

The earlier studies indicated that the most abundant clay minerals in the near-surface soils of volcanic rock origin are the kaolin group of minerals. Both kaolinite and halloysite are formed mainly from the decomposition of feldspars, which are abundant in these rocks. Halloysite is more common in saprolitic soils, co-existing with a minor quantity of kaolinite. This is to be expected as these soils have been formed on well-drained sideslopes of the mountainous terrain in Hong Kong under a prolonged subtropical climate. Halloysite and kaolinite may give way to gibbsite under advanced weathering conditions close to the top of the weathering profile, particularly in residual soils (Lumb & Lee, 1975; Irfan, 1996b). A small amount of the swelling mineral vermiculite may also be present (Parham, 1969). Allophane has been identified in volcanic rocks, at least in the initial stages of decomposition of feldspars, but it then rapidly changes to halloysite with further decomposition (Lumb & Lee, 1975). Recently, Irfan (1994) published the results of chemical, mineralogical and fabric analyses of coarse ash tuffs from a landslide site in Hong Kong. The results have been incorporated into this document.

6. METHODS OF THE PRESENT STUDY

The study undertaken on the volcanic rocks was less comprehensive than that in a similar study of granitic rocks (Irfan, 1996a). The principal aim of the study is to establish the basic mineralogy and fabric properties of selected weathered rock types, mainly the tuffs. The following methods were used to determine the mineralogy and microfabric of the volcanic rocks:

(a) Detailed description of hand specimens.

(b) Optical microscopy on thin sections to determine and quantify the mineralogy and fabric properties (e.g. grain boundary relationships, voids, weathering state of the mineral constituents and their arrangement).

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

(d) X-ray diffraction (XRD) analysis, on bulk samples and clay fractions.

Brief description of the methods of analysis used by the four laboratories which carried out the analyses under items (c) and (d) is given in Appendix B. The comments by these four laboratories and the author on the accuracy of identification of various minerals from the techniques used are also given in Appendix B.

7. DESCRIPTION OF SAMPLING LOCATIONS AND WEATHERING CHARACTERISTICS

7.1 Fine Ash Tuff, Ap Tsai Wan, Tsueng Kwan O

The sampling site is situated on a ridge at Ap Tsai Wan headland, north of the town of Tseung Kwan O (Figure 4). The headland is composed of fine ash tuff, eutaxite and tuff breccia of the Ap Lei Chau Formation. The site has recently been formed into a series of cut slopes.

The saprolitic layer is about 15 m thick on the site but the residual soil layer is missing, at least along the ridge line. There is a regular layering of the mass weathering grades at the truncated headland with the core of the hill composed of fresh to slightly weathered fine ash tuff and eutaxite. The regular layering is disturbed by fault zones where weathering penetrates to greater depth (Plate 4).

Hand and block samples were collected from the different material grades at the site with the more weathered specimens obtained from higher levels in the cut slopes. Brief descriptions of hand samples are given in Appendix A.

7.2 Fine Ash Tuff, Tseung Kwan O

The sampling site is situated at an elevation of about 130 mPD on the mid-slopes of Tai Sheung Tok (elevation 400 m), west of Tseung Kwan O (Plate 5). Volcanic soil from this site was used to assess the effect of matric suction on direct shear strength of Hong Kong soils by Gan & Fredlund (1992).

The site is underlain by fine ash vitric tuff of the Ap Lei Chau formation. The weathering profile is variable and relatively thin at the site (Figure 5). Only the upper portion of the weathering profile is exposed along the 5 m high road cutting where the samples were taken. A layer of mottled brown and yellowish brown residual soil is present in some places underneath a thin colluvium layer. The transition from residual soil to saprolitic soil is irregular but generally occurs within a metre from the ground surface. The presence of white kaolin veins along certain discontinuities within the rock may indicate hydrothermal alteration.

Corestones are present but poorly developed.

Three block samples were used for the direct shear strength research and mineralogical and microfabric studies were conducted on hand specimens representing different weathering grades. Brief descriptions of the samples are given in Appendix A.

7.3 Coarse Ash Tuff, Sai Kung

The sampling site is situated in a disused borrow area on top of a small isolated hill (elevation of 60 mPD), on a small peninsula in Sai Kung (Figure 1). The site is underlain by coarse ash crystal tuff, originally mapped as belonging to the Tai Mo Shan Formation by Strange et al (1990), now referred to as Sai Kung Formation.

The thickness of saprolitic soil at the site is not known. However, it is considered to be over 10 m thick, based on the coastal exposures of weathered rock. The residual soil layer is thin, less than 1 m, and irregularly developed. The rock shows typical spheroidal type of weathering commonly associated with the coarse-grained tuffs in the Territory (Plate 6). Numerous corestones, usually less than 0.5 m in diameter, are present in the saprolitic soil and occasionally in the residual soil.

A limited number of specimens were collected from the saprolitic and residual soil zones. Fresh to moderately decomposed samples were obtained from the corestones in the saprolitic soil. Brief descriptions of the samples are given in Appendix A.

7.4 Coarse Ash Tuff, Aberdeen

The sampling site was originally a minor ridge crest on the southern footslopes of a northeast-southwest trending major ridge in Aberdeen. Borrowing activity in the 1920s resulted in removal of the colluvium cover and top few metres of the saprolitic-residual soil layer and the formation of two dish-shaped areas.

A shear plane, formed at a depth of about 4 m in the saprolitic soil as a result of continuous creep, acted as the release surface for a landslip in 1988. A petrographical study of the weathered rocks in the slope was undertaken to determine the causes of the creeping behaviour (Irfan, 1992, 1994).

The coarse ash tuff is deeply weathered on the site, with the saprolitic soil zone 15-20 m thick (Figure 6). Numerous white clayey veins criss-cross the saprolite. The layer above the pre-existing shear plane consisted of soft mottled volcanic soil with a deformed tuff fabric. A thin transition soil layer was observed above the saprolitic soil.

Samples for the mineralogical study were collected from various soil materials on the site as well as the less weathered rock grades recovered as cores from the boreholes (Plate 7). Brief descriptions of the samples are given in Appendix A.

7.5 Coarse Ash Tuff, Yuen Long

The sampling site is a newly formed cut slope adjacent to a haul road in Tai Tong East borrow area, south of Yuen Long (Figure 1). The slope, 30 to 50 m high with a gradient of about 30°, was formed in early 1991 by cutting into the natural hillside. The slope was subject to instability soon after cutting in June 1991. The instability is confined to a thin layer of volcanic rocks which overlie a fine-grained granite.

The volcanic rock at the site, mapped as undifferentiated tuff and tuffite on the new geological map, is a lapilli-bearing coarse ash crystal tuff of the Shing Mun Formation. The rock is rich in quartz crystals, up to 5 mm in diameter, and mica (up to 10%) but poor in feldspar crystals. It is probably contact-metamorphosed by the granite.

The tuff above the granite contact is completely to highly weathered. The granite shows less intense weathering, at least where it is exposed along the cutting. Occasional corestones are present in the saprolite but these are not well developed unlike other coarse ash tuffs in the Territory. The topmost layer of the saprolitic zone shows a highly deformed fabric and structure where it has been affected by recent slope movements.

Only five samples were collected from the site, with two each from the highly decomposed and completely decomposed tuff and one 'fresh' sample from inside a corestone. Details of the samples are given in Appendix A.

8. DESCRIPTION OF MATERIAL WEATHERING GRADES IN TUFFS

8.1 General

The material weathering grade scheme adopted in this document follows Irfan (1996a). However, subdivisions based on relative strength values have not been attempted for these volcanic rocks due to lack of laboratory and insitu data. Plates 8 to 10 illustrate the various material grades in fine ash and coarse ash tuffs.

8.2 Fresh Rock

Fresh Fine Ash Tuffs are usually medium grey to dark grey but also light grey or black, and extremely strong. These rocks generally consist of a small amount of euhedral to subhedral broken crystals of feldspars or quartz or both and occasional vitric fragments in a very fine vitric (glassy) matrix. If fiamme are present, then the rock is called 'eutaxite'. The matrix may be finely recrystallized, particularly if the rock is metamorphosed.

Fresh Coarse Ash Tuffs are usually bluish grey to dark grey and very strong to extremely strong. They generally comprise abundant crystals of feldspars (up to 3-4 mm in size) with some quartz and biotite and occasional lithic fragments in a fine-grained vitric to recrystallized matrix. Welding fabric may be present in the matrix.

8.3 Slightly Decomposed

Subdivisions can be made within this grade for fine and coarse ash tuffs (and for volcanic rocks in general) based on the degree of discoloration (Plates 8 to 10), similar to the subgrades suggested for granitic rocks. Discoloration is usually an indication of weathering.

Slightly Discoloured: The rock material is discoloured less than 10% by volume from joint and fracture surfaces inwards to yellowish grey to yellowish brown. The interior of the joint-bounded block retains its original grey to dark grey colour.

Moderately Discoloured: The rock material is discoloured 10% to 50% by volume to yellowish grey to light grey with dark brown in the vicinity of fractures and joints. The fresher centre may show very light grey discoloration.

Highly Discoloured: The rock material is discoloured more than 50% by volume. Colour banding may be present with medium grey fresher centres surrounded, in turn, by light yellowish grey, yellowish grey and dark brown rims. The same concentric colour banding may also be present in corestones which are commonly present in the saprolitic zone in coarse ash tuffs, with the outermost layers being highly to completely decomposed. In the corestones, feldspars become progressively softer (more decomposed) towards the exterior. There is also development of concentric microfractures in the discoloured rim in both coarse ash and fine ash tuffs, which increases in intensity towards the exterior of a corestone or a joint-bounded block in this subgrade.

8.4 Moderately Decomposed

The rock material is completely discoloured, light yellowish to yellowish greenish grey. The joint surfaces may be stained reddish brown to dark brown. The rock is very strong when least weathered to moderately weak when most weathered within this grade. Some feldspar crystals are gritty, particularly in the most weathered tuff specimens. Near joint surfaces they may be gritty to soft. Biotite, if present, is dull greenish grey and soft. The rock fabric is fractured throughout by a network of tight but iron-oxide stained microcracks.

8.5 Highly Decomposed

The rock material is completely discoloured, light yellowish grey or greyish yellow with yellowish brown near joints and fractures. The strength is very much reduced due to extensive microcracks. Feldspar crystals are largely gritty, some hard (in the weak rock range) to powdery and occasionally soft (in the extremely weak rock range).

8.6 Completely Decomposed

This grade of weathered tuff could be divided into subgrades similar to those for granitic rocks, based on the type and degree of alteration and weathering and the relative density (strength), but this has not been attempted here.

The rock material is discoloured throughout to yellowish grey, yellowish greenish grey or reddish brown, and it can also be mottled. Pinkish grey and white patches can be present locally if it is affected by hydrothermal alteration, usually in the vicinity of kaolin or kaolin-quartz veins. Differential weathering may be present between the lithic fragments and the matrix in lapilli-bearing tuffs. Feldspar crystals are usually powdery to soft with degree of decomposition being more intense than in the hydrothermally altered areas. Quartz, if present, is dull and biotite is transformed into colourless to silvery grey flakes. The completely decomposed specimens can be easily disaggregated into soil particles by finger pressure.

8.7 Transition Soil

Transition soil specimens are usually dark reddish brown, but may also be mottled with patches of yellowish grey. The soil shows partial loss of the tuff fabric, the proportion of which increases up the weathering profile. Relict discontinuities are largely absent in the transition soil zone. Occasional partially decomposed feldspar crystals may be present in areas still retaining the original tuff fabric.

8.8 Residual Soil

The specimens are usually yellowish brown, but may also be yellowish grey when bleached of its iron minerals. The soil comprises some sand-size quartz grains in a structureless clayey silt to silty clay matrix. Nodules or pods of iron-oxide cemented soil aggregations may be locally present. In extreme cases, cementation by iron-oxides and hydroxides may produce a weak rock (i.e. a laterite).

9. MINERALOGY AND FABRIC CHARACTERIZATION OF WEATHERED TUFFS

9.1 General

The textural and mineralogical properties of volcanic rocks in Hong Kong are very variable depending upon the type of volcanic activity and subsequent processes which formed these rocks, the mode and history of solidification and later metamorphism, hydrothermal and other alteration processes. As a result, wide variations in texture and mineralogy can even occur in the same rock type at each location (Table 2).

Coarse ash tuffs occur in many formations. In general, they consist of crystals or crystal fragments of feldspar and quartz, up to 6 mm in size, with small biotite and occasional hornblende and secondary muscovite set in a fine-grained matrix of the same minerals. Clasts of sedimentary or igneous rocks of various sizes may also be present. The matrix may be partly or wholly recrystallized, particularly in the vicinity of granite intrusions. Some crystal alignment and weak to strong welding fabric with elongate recrystallized siliceous shards and fiamme may be present. Crystal tuffs of the Shing Mun Formation are particularly variable in grain size and texture and can show rapid variation both laterally and vertically from coarse ash to fine ash to lapilli tuffs. The total crystal content can vary from 20% to over 50%.

Feldspar crystals are particularly abundant in Tai Mo Shan and Yim Tin Tsai tuffs. Quartz grains may be rounded to broken and angular, occasionally resorbed with no clearly defined grain boundaries. Biotite occurs as individual large grains as well as small aggregations scattered throughout the groundmass. It is usually partially chloritised. Alkali feldspars may be cloudy and partly replaced by epidote. Plagioclases may be slightly sericitized even in the fresh rock. These mineralogical changes are probably the result of sub-aerial processes during the formation and solidification of the rock as well as the later hydrothermal activity from intruding granites.

Fine ash tuffs including eutaxites are particularly common on Hong Kong Island and in the vicinity of Junk Bay and Sai Kung. They generally consist of a small amount of scattered crystals (up to 20% of the rock), dominantly quartz with some feldspars and occasional lithic fragments, in a very fine vitric (glassy) matrix (Strange & Shaw, 1986). The matrix may be finely recrystallized, particularly in the vicinity of igneous intrusions. In the eutaxites, a welding compaction structure arising out of alignment of flattened fiamme, stretched pumice and lithic fragments is present. Majority of crystals are usually broken and often resorbed with in distinct grain boundaries.

The crystal-bearing fine ash welded tuffs which occur in the vicinity of High Island display well-developed columnar jointing (Strange et al, 1990). The quartz and feldspar crystals comprise up to 20% of the rock in a very fine-grained or vitric groundmass. Quartz crystals are invariably corroded and resorbed. Feldspars occur as euhedral grains or broken crystal fragments. The fine ash tuffs of the Silverstrand Formation have prominent eutaxitic fabric. Fiamme is usually abundant comprising up to 30% of the rock. Lenses of sedimentary rocks and chert fragments may be abundant at some localities.

In the following sections, a brief summary is given of the mineralogical and fabric properties of the volcanic rocks weathered to different degrees, with particular emphasis on the fine ash and coarse ash tuffs as these were the only rocks studied in detail in this study.

The mineralogical compositions of the freshest specimens from the five rock types are given in Table 3, with the results of quantitative petrographical determinations shown in Tables 4 and 5. The results of chemical analyses, arranged in order of weathering grade, are given in Tables 6 to 8. The results of XRD analyses on bulk and clay fractions are presented in Tables 9 to 14 in terms of the relative abundances of minerals identified from the traces. Figures 7 to 10 show the typical XRD traces for selected specimens. The bulk norm mineralogies calculated from the results of chemical analysis using the mineral types identified by XRD are given in Tables 15 to 17. Schematic representations of the mineralogical changes occurring with weathering in each of the five tuffs are given in Figures 11 to 15. Plates 11 and 12 are micrographs illustrating the typical mineralogical and fabric properties of fine and coarse ash tuffs weathered to various degrees.

Quantitative petrographic analyses were not carried out for the finer tuffs due to the difficulty in recognising the minerals and voids, particularly in the weathered specimens. Comments on the identification of minerals from the XRD analysis and on the accuracy of the chemical analyses results are contained in Appendix B.

9.2 Fresh Rock

The fine and coarse ash tuffs included in the study are all rhyolitic in composition. The major constituents are feldspars and quartz with some mica occurring as large euhedral crystals or crystal fragments in a devitrified or recrystallized groundmass of the same minerals. Occasionally, lithic fragments are also present. The crystal content reaches over 50% in the case of coarse ash tuff from Aberdeen, but in the fine ash tuffs it is usually less than 25% of the rock (Table 4). Feldspars are the dominant constituents with plagioclase being more abundant than alkali feldspar. Overall, quartz contents vary between 25% and 45%. However, the quartz crystal contents are usually low, less than a few percent, except in the coarse ash tuff from Aberdeen it reaches 15% of the rock. The chemical analysis and optical microscopy revealed that the specimen ATW1 from Ap Tsai Wan has a significantly different chemical and mineralogical composition than the other specimens collected from the same site (Table 8).

Biotite, when present, is mostly partially to completely altered to a mixture of hydrous mica, chlorite, iron oxides and sometimes to vermiculite. The mica content of the coarse ash tuffs from Yuen Long is rather high (about 10%). Small amounts of secondary minerals such as muscovite, hydrous mica, chlorite, occasionally calcite, and in some cases, kaolinite are invariably present in addition to minor amounts of iron-oxide minerals, mainly magnetite. The majority of secondary products is attributed to probable effects of epigenetic processes during or subsequent to volcanism and solidification. Later effects of contact metamorphism and hydrothermal alteration by the intruding granitic magmas might also have contributed to the formation of micaceous minerals in these rocks.

In thin section, most plagioclases and some alkali feldspars show slight to moderate alteration to micaceous products (commonly termed sericite) in all five tuffs. Calcite also occurs in some crystals and also in the groundmass, possibly as a byproduct of breakdown of Na-Ca plagioclase to micaceous minerals and kaolinite. Fine-grained micaceous minerals and chlorite also occur in the groundmass. The fresh rock is unfractured except for occasional short and tight microcracks in quartz and feldspar crystals.

The tuff from Aberdeen has the coarsest grain size, with quartz and feldspar crystals, up to 4 mm in diameter. The fine ash tuff from Ap Tsai Wan has a strong eutaxitic foliation. A faint flow fabric is also present in the tuff from Tseung Kwan O.

9.3 Slightly Decomposed

Noticeable decreases occur in Na^+ and Ca^{2+} contents which indicate the commencement of decomposition of Na - Ca feldspars (plagioclases) in the slightly decomposed tuff grade. The behaviour of K^+, Si^{4+} and Al^{3+} are not so predictable and, in some cases, these cations show increase or decrease against the expected trend with increased weathering. For example, K^- and Si^{4+} contents are higher than those of the fresh rock in some of the slightly decomposed specimens (Table 8). These variations are attributed to variations in the chemical and mineralogical composition of the original rock within each sampling site including those arising from hydrothermal and other alteration processes.

The carbonate minerals, which may be present in small amounts in fresh tuffs, are largely removed by solution in this grade as indicated by significant reduction in CO_2 and Ca^{2+} contents, although most of the reduction in the latter is probably due to decomposition of Ca-bearing feldspars. The optical microscopy revealed void formation within some feldspars and in the groundmass at the locations of calcite, especially in the stained portions of the specimens.

In thin section, a small amount of feldspar decomposition, mainly to micaceous minerals, is present even in the fresher portions of the specimens. The degree of decomposition of feldspars increases in the stained rims, especially in plagioclase megacrysts. There are variations in the type and intensity of feldspar weathering amongst the tuffs. For example, all feldspar megacrysts show slight to moderate degrees of decomposition in the tuffs from Sai Kung, Tseung Kwan O and Ap Tsai Wan as reflected in their calculated mineralogies (Tables 16 and 17), but the plagioclases are only slightly decomposed and the alkali feldspars are not generally affected by weathering in the coarse ash tuffs from Aberdeen. The moderately and highly decomposed specimens show an increase in the calculated alkali feldspar content (Table 15). This is considered to be mainly due to the higher alkali feldspar contents of these specimens.

In the stained rims, some areas within the partially altered feldspars appear 'cloudy' or 'speckled'. These could be poorly crystalline alumina-silicate minerals transitional to kaolinite or halloysite. They might also be the locations of solution pits indicating the onset of solution weathering (Dearman & Baynes, 1978; Irfan, 1996b). Slight to noticeable solution of feldspars was observed by Kwong (1988) in slightly to moderately decomposed volcanic rocks from Hong Kong Island using electron microscopy. Reddish brown staining of the rock fabric by iron-oxides without any apparent microfracturing might also be taken as evidence of solution in the feldspar megacrysts and also the groundmass.

Biotite, shows partial to complete alteration to a mixture of secondary products including hydrous mica, chlorite, iron-oxides and sometimes vermiculite. The trace amounts of chlorite, hydrobiotite and vermiculite or intermixed chlorite-vermiculite identified by XRD in some tuffs are considered to be formed from the alteration of biotite. The presence of chlorite and vermiculite also occurring in the unweathered rock suggests that these minerals are largely formed by hydrothermal processes although vermiculite and hydrobiotite can also form from weathering of biotite in well-drained conditions in humid climates (Gilkes & Suddhiprakaran, 1981).

The feldspars in the devitrified groundmass also show increased decomposition with increased staining where the groundmass assumes a semi-opaque appearance under the microscope. In the case of tuffs with eutaxitic texture, staining is more intense along bands that also show more intense alteration.

Trace to small amounts of kaolin minerals were identified by XRD in the discoloured portions of specimens in some tuffs (Tables 10 and 11). Kaolin minerals are also present in the fresh rock or unstained portion of some of the specimens, which suggests that the majority of kaolin minerals present in the fresh and slightly decomposed tuffs are formed by pre-weathering processes such as hydrothermal alteration. The predominant kaolin mineral is kaolinite with only trace amounts of halloysite in the more weathered specimens of the slightly decomposed grade. The halloysite content increases in the moderately and highly decomposed grades, suggesting that this mineral is formed directly from the decomposition of feldspars in intermediate stages of weathering. The increase in kaolin content in the discoloured portions and in the moderately decomposed specimens is mostly derived from the alteration of plagioclases as the alkali feldspars do not show any significant petrographic change.

A trace amount of a possible smectite mineral was indicated in the coarse ash tuff from Aberdeen in addition to minor amounts of chlorite and vermiculite or an intermediate mineral between the two (Table 9). The hydrothermal alteration of the rock might have resulted in the formation of metastable smectite in the initial stages of feldspar alteration, as well as formation of chlorite and vermiculite from alteration of biotite (Irfan, 1994).

The total amount of secondary minerals varies, up to 12% or even more in the slightly decomposed tuffs. The proportion of microcracks and pores is very low, usually less than 1 % by volume.

A network of simple-branched and tight but mostly iron-oxide infilled or coated microcracks is developed in the stained portions. The frequency of microfracturing increases towards the joint surfaces. The boundaries of quartz and feldspar megacrysts are tight in the fresher cores but they may be coated with iron-oxides in the stained rims. The staining or coating along grain contacts may indicate the development of intergranular fracturing or the formation of dissolution pits and channels around the exterior of the larger feldspar grains, as identified by Kwong (1985).

9.4 Moderately Decomposed

Rapid reductions occur in Na^+ and Ca^{2+} contents with the exception of the coarse ash tuff from Yuen Long (Tables 6 to 8), indicating a significant decomposition of plagioclase. The associated increases in clay mineral contents are reflected in LOI values which are almost double those of the slightly decomposed tuff. These changes are confirmed by XRD results, which show that the kaolin mineral content in this grade is increased significantly from a few percent to up to 20% or more (Tables 15 to 17). No consistent change is apparent in K^+ content indicating that the alkali feldspars are not yet significantly affected by weathering in this grade.

Although there is a sharp drop in Na^+ content as the rock weathers from the slightly decomposed to the moderately decomposed state, the Ca^+ content is unaffected in coarse ash tuff from Yuen Long (Table 7). This might be due to the presence of calcite as indicated by the high CO_2 content or absence of Ca- bearing feldspars in this rock type.

Optical microscopy revealed that the majority of large plagioclase grains are decomposed to kaolin and micaceous minerals, with alkali feldspars only slightly affected but generally highly microfractured. The feldspars in the fine-grained to cryptocrystalline groundmass also appear to be affected by weathering in this grade. Numerous isotropic speckles were observed in many large feldspars under the microscope, similar to those identified in granites (Irfan, 1996b). These are probably either the locations of solution pits and trenches observed by Kwong (1985) and Dearman & Baynes (1978), or some intermediate alumina-silicate growths transitional to kaolin minerals.

The main kaolin mineral is a poorly crystalline kaolinite with a possible trace amount of halloysite only detected in the tuff from Tseung Kwan O. Parham (1969) also reported the growth of flame - shaped films and halloysite tubes on feldspars in some slightly to moderately decomposed rhyolite- porphry specimens (probably a coarse ash tuff).

In addition to kaolin minerals, small amounts of sesquioxides, vermiculite and chlorite were identified in some rocks from the XRD patterns. A trace amount of a smectite mineral, or an interstratified clay mineral of possible illite-smectite composition, was also detected in the tuff from Aberdeen. The quantitative modal and mineralogical analyses show that the clay and micaceous mineral content can be up to 25% in this grade (Tables 15 to 17).

The most significant change in the rock is the formation of an extensive network of tight to slightly open microcracks in this grade. As a result, a fairly rapid reduction in intact strength occurs across the grade. Most large feldspars and some quartz grain boundaries are stained which indicate that the grain boundaries are opening up. Apart from the pores formed at the locations of dissolved calcite grains in some specimens, solution features have not been observed under the microscope.

9.5 Highly Decomposed

Fairly rapid changes occur in the major oxides contents within the highly decomposed grade (Tables 6 to 8), indicating more intense decomposition and more rapid variation of the clay mineral content of the volcanic rocks in this grade than in the moderately decomposed grade. Both Na^{-} and Ca^{2+} contents are reduced to very small values in all rock types except the coarse tuff from Yuen Long, with complete disappearance of plagioclase in the more intensely weathered specimens as confirmed by XRD and optical microscopy. A noticeable reduction in K^{+} content in all rock types except the tuff from Aberdeen indicates that alkali feldspars are now being affected by weathering within this grade. The Si^{4+} content also shows a noticeable reduction except in some hydrothermally altered specimens (Tables 7 and 8).

Both feldspar types show variations in their degree and type of alteration. Plagioclase contents are less than 3% in the fine ash tuffs, but can be up to 17% in the coarse ash tuff from Yuen Long. Although plagioclases show near-complete alteration, the type of clay fabrics formed can be different in each rock. For example, the decomposed feldspar pseudomorphs are very porous in the coarse ash tuff from Aberdeen in comparison to the dense clay fabrics produced in the coarse ash tuff from Sai Kung. The altered feldspars in the specimens affected by hydrothermal alteration have, in general, more clayey, denser microfabrics than those affected only by weathering.

Alkali feldspars are little altered in the tuff from Aberdeen, but they are intensely microfractured. In contrast, the tuffs from Sai Kung and Tseung Kwan O are highly decomposed to clay minerals. The intensive solution of alkali felspars generally occurs in the completely decomposed grade (Plate 11). The decomposition of feldspars in the groundmass is more advanced in this grade than in moderately decomposed tuff, with specimens unaffected by hydrothermal alteration having more porous groundmass than those affected. The groundmass is particularly porous in the tuff from Aberdeen.

Kaolin minerals are the dominant clay minerals, with small to accessory amounts of micas and trace amounts of chlorite and vermiculite or intermixed chlorite-vermiculite in some rocks (Tables 15 to 18). Kaolin minerals in the fine ash tuffs form up to 40% of the rock and even more in the altered specimens, but generally less than 25% in the coarse ash tuffs. The coarse ash tuffs have similar kaolin contents to granites (Irfan, 1996a). The halloysite content generally increases in this grade but not in all rock types. It forms up to half of the kaolin content in tuffs from Aberdeen and Ap Tsai (Tables 12 and 14). Halloysite was not detected in tuffs from Sai Kung and Yuen Long. Due to the lack of detailed electron microscope studies it is not known whether the halloysite in the coarse ash tuff from Aberdeen is formed directly from the decomposition of feldspars or through an intermediate mineral. Kaolinite may form (i) by hydrothermal alteration of feldspars, (ii) by direct transformation of feldspars, or (iii) through an intermediate alumina-silicate mineral. It is possible that all three sources have contributed to kaolinite formation in the weathered volcanic rocks. A small amount of kaolinite might also have formed from the decomposition of biotite. Trace amounts of vermiculite or an intermediate vermiculite-chlorite identified by XRD in the tuff from Aberdeen. It is highly likely that it is formed from alteration of biotite. Small amounts of sesquioxides occur in all rocks, generally as poorly crystalline aggregations. Thermogravimetric analysis indicates that these are mostly goethite.

The rock fabric is extensively microfractured by tight to slightly open microcracks, which together with voids comprise up to 20% of the rock in tuffs from Aberdeen (Table 5). Some disturbances of the fine-grained groundmass in the vicinity of the microfractured quartz and feldspar grains indicate a slight expansion of the rock at this stage of weathering.

9.6 Completely Decomposed

In spite of the differences in their chemical and mineralogical compositions and textures, the completely decomposed fine and coarse ash tuffs show many similar mineralogical and fabric characteristics in the completely decomposed grade. However, significant differences can also occur, even in the same rock type, if the rock has been subjected to hydrothermal and other alteration processes prior to weathering. Variations in the present-day weathering environment can lead to significant differences in void characteristics and clay mineralogy of the soil formed from the same rock at different locations.

Plagioclases are completely decomposed in this grade in coarse ash tuffs from Aberdeen and Ap Tsai, whilst complete decomposition of plagioclases occur in the highly decomposed grade in all other tuffs studied. The Ca^{2+} and Na^{+} contents are further reduced to very small amounts compared with highly decomposed tuffs, indicating the removal of cations from the soil, except in the tuff from Yuen Long where the Ca^{2+} content is still appreciable (Table 7). This is attributed to the accumulation of Ca-bearing minerals (e.g. calcite) in the soil or absorption of freed Ca^{2+} by other mineral species rather than the presence of unaltered Ca-bearing plagioclases.

Significant reduction in K^{+} content in all completely decomposed tuffs compared with highly decomposed tuffs indicates intense weathering of alkali feldspars within this grade (Tables 6 to 8). Nevertheless, there are variations in the way the alkali feldspars decompose (e.g. solution versus alteration to clay minerals), depending on the environment of weathering and the degree of hydrothermal alteration or contact metamorphism. For example, the tuffs underlying gentle hillslope environments where active removal of cations by migrating groundwater occurs (e.g. Aberdeen coarse ash tuff, Tseung Kwan O fine ash tuff), show widespread solution type weathering with advanced honeycomb fabric development in the coarse ash tuffs (Irfan, 1994). The groundmass in these rocks also assumes a highly porous appearance.

Although the Yuen Long site has also a relatively gentle hillside topography, the completely decomposed tuff specimens from this site do not have the highly porous fabrics displayed by Aberdeen tuffs. This might have been the result of contact metamorphism of the tuff by the underlying granite at this site, which had resulted in the formation of kaolinite and micaceous minerals in the fresh rock. Kaolinite, being a stable mineral would not be subject to solution type weathering, which usually results in the removal of cations, particularly from the feldspars. The tuffs from Aberdeen also show the effects of kaolinisation and sericitization due to hydrothermal alteration, but these appear to be restricted to the vicinity of kaolin or kaolin-quartz veins (Irfan, 1994).

The results of quantitative mineralogical analysis are in general agreement with the observations made on thin sections. For example, the unaltered alkali feldspar content is reduced from about 13 to 19% and 27% in the highly decomposed tuffs from Ap Tsai and Aberdeen respectively, to less than 8% in the completely decomposed tuffs from both sites. The alkali feldspars in the completely decomposed specimens from Sai Kung, which has a coastal low hilltop environment, show chemical decomposition to clay mineral products (mainly kaolinite).

Biotite usually occurs in a completely altered state comprising a mixture of fine aggregations of hydrous mica, chlorite, kaolin minerals and iron-oxides. The altered mineral structure shows evidence of expansion and, in some cases, complete disaggregation into smaller grains.

The kaolin mineral content increases sharply to up to 50% in this grade and particularly in the more intensely weathered specimens (Table 17). Halloysite becomes almost as abundant as kaolinite in the least weathered specimens in this grade, being particularly abundant in the coarse ash tuff from Aberdeen (Table 12), concentrations being similar to granites (Irfan, 1996a, b). However, in the completely decomposed tuffs from Sai Kung and Yuen Long, only small amounts of halloysite were detected in the clay portions (Table 13). There may be a number of reasons for the dominance of kaolinite in these two rock types, some of which are given below :

(i) The contribution from direct alteration of alkali feldspars to kaolinite. The alkali feldspars show widespread decomposition to kaolinite rather than solution type weathering in this grade.

(ii) Direct formation of kaolinite from pre-weathering processes such as contact metamorphism and hydrothermal alteration. The tuffs at both sites show evidence of contact metamorphism, with the granite immediately underlying tuff at Yuen Long.

(iii) Poor drainage in a low-lying coastal topography at Sai Kung might also have inhibited the formation of halloysite.

(iv) Most halloysite may be of silt size, as is the case with granites (Irfan, 1996b), and hence is not present in the clay portions analysed.

In the more intensely weathered completely decomposed specimens and in the transition soil grade, kaolinite becomes dominant with only small amounts of halloysite (Tables 12 to 14).

The other alteration products include trace to small amounts of fine-grained micaceous minerals, sesquioxides and, in some rocks, small amounts of vermiculite or chlorite. The chlorite content appears to decrease with increased weathering. Chlorite was not detected in the completely decomposed and residual soil specimens from some sites. Gibbsite was also not identified in the XRD traces of any of the specimens in this grade. The micaceous products were identified by XRD as mostly illite in tuffs from Aberdeen based on the line broadening and relative peak heights (Appendix B).

The weathered rock shows extreme fabric variations in the completely decomposed grade. In general, very fractured and porous fabric is developed in the coarse-grained tuffs from hillside environments. Generally, denser clayey fabrics are formed in the fine-grained tuffs and those rocks previously affected by contact metamorphism or hydrothermal alteration. Poorly drained conditions, for example, in valley bottom type environments, may also lead to generally clayey fabrics. The cementation by iron-oxides may locally be very intense and so obliterates the soil fabrics. Organic matter may also be present in some specimens, as reflected in their higher than usual carbon contents.

9.7 Transition and Residual Soil

The most significant chemical change is in K^+ content where it decreases appreciably within the residual soil stage, indicating intense decomposition of alkali feldspars. However, the K^+ content is still significant in the residual soil specimens of the fine ash tuff from Tseung Kwan O and the coarse ash tuff from Sai Kung (Tables 7 and 8). As the alkali feldspars are completely decomposed, the major contribution to K^+ content is from kaolinite, which now forms over 50% of the total soil weight. The increased decomposition of alkali feldspars to clay minerals indicates that chemical alteration of these feldspars takes place at a very advanced stage of weathering, subsequent to solution weathering in the initial and intermediate stages. The other important chemical change is in Si^{4+} content which shows a noticeable reduction for the first time in this grade indicating a noticeable solution of quartz. The XRD traces and semiquantitative calculations confirm some reduction in quartz content in agreement with the microscopical observations (Tables 16 and 17). The reduction in silica or quartz content may also be due to hydrothermal effects.

Halloysite content decreases significantly in the transition soil and disappears completely in the residual soil derived from tuffs. The halloysite in this advanced stage of weathering was identified as the dehydrated type. Lumb & Lee (1975) attributed the formation of dehydrated halloysite in near-surface volcanic soils to considerable seasonal desaturation, together with a much greater chance of oxidation resulting eventually in complete dehydration to kaolinite.

In addition to predominant kaolinite and trace amounts of halloysite, small amounts of micaceous minerals (illite and muscovite), trace chlorite and, in some soils, vermiculite and possibly interstratified clay minerals of illite-smectite composition are present. Small quantities of gibbsite was reported by Lumb & Lee (1975) in near-surface volcanic soils and by Irfan (1996b) in residual granitic soils. Gibbsite has not been identified in any of the volcanic soils analysed here. In some soils, small amounts of CO_2 were detected. This is attributed to the presence of organic matter in the specimens. There is a small increase in the total iron-oxide content, which forms up to 8% of the soil. The dominant iron mineral present in the volcanic soils was identified by thermogravimetric analysis as poorly crystalline goethite with haematite in some specimens.

The original rock fabric gradually disappears within the transition soil grade and the residual soil comprises some silt-to sand-size quartz grains (usually less than 20% of the soil) in a structureless clay mineral-iron oxide mineral matrix. The coating and cementation by iron minerals are so intense, locally, that the details of soil fabric may be completely obliterated. Occasional large pores, some of which are ant holes and decayed root locations, are present. Microcracks are much reduced in amount and most are secondary features, e.g. desiccation cracks. There may be small aggregations or 'pebbles' of reddish brown iron-oxide minerals throughout the soil fabric and these may be taken as an indication of commencement of laterization at some sites.

9.8 Iron-oxide Minerals in Volcanic Saprolites and Residual Soils

There are variations in the iron-oxide contents of the saprolitic and residual specimens analysed, as reflected in their Fe_2O_3 contents, depending on the degree of weathering and the location of the specimen within the weathering profile. Generally, the iron-oxide content is less than 10%. However, it may be higher in areas of iron-oxide concentration, e.g. in the groundwater fluctuation zone, as was the case with the Aberdeen landslide site (Irfan, 1994).

In thin section, iron minerals generally appear as poorly crystalline aggregations scattered throughout the groundmass, but also as coatings to partially to completely decomposed minerals, or as microcrack infillings. Locally, weak cementation is also present.

Detailed studies on granitic rocks indicated that goethite is the main iron-oxide mineral formed via ferrihydrite or directly from the decomposition of biotite in the intermediate and advanced stages of weathering (Irfan, 1996a). This is probably the case for the coarse ash tuffs and most other volcanic rocks in Hong Kong. However, the lack of any weight loss between 200° and 400°C in the thermogravimetric analyses of specimens from Sai Kung and other volcanic rock sites (except Aberdeen) were interpreted as these rocks not containing any detectable goethite or gibbsite by one of the laboratories (British Geological Survey). Haematite was considered to be the main iron mineral present in the weathered tuffs from these sites. The tuffs from Sai Kung contain some magnetite. Diffuse magnetite boundaries may indicate the commencement of alteration to haematite in the moderately to highly decomposed stage. Thermogravimetric analyses carried out for Aberdeen specimens indicated the presence of poorly crystalline goethite. In granites, Irfan (1996a) reported that the crystallinity of goethite increased with weathering. This might also be the case for volcanic rocks.

9.9 Kaolin Veins

The XRD analysis of a number of kaolin veins taken from the landslide sites on Hong Kong Island (Irfan & Woods, 1997) show that these veins contain dominantly kaolinite with some illite and quartz and, in some cases, a smectite mineral (Table 18). Optical microscopy indicates that there may be an increase in the micaceous alteration products (mainly formed within the feldspars) adjacent to these veins and in the 'pink feldspar' areas. This may represent the situation described by Sales & Meyer (1940) that in the vicinity of hydrothermal veins in igneous rocks, a zonal arrangement of clay minerals may occur, with a sericitic mica zone immediately adjacent to the vein followed by kaolinite and smectite - chlorite zones. Small amounts of swelling minerals (smectite) were identified in the weathered rock from Aberdeen, in addition to up to 15% smectite identified in some of the veins. It is also possible that smectite may have formed from weathering processes in a poorly drained environment, but this is considered unlikely for the Aberdeen site.

10. CLASSIFICATION OF WEATHERED VOLCANIC ROCKS AND SOILS IN HONG KONG

10.1 Classification of Material Weathering Grades of Volcanic Rocks

A characterization of the material grades of volcanic rocks (primarily the tuffs) in Hong Kong is given in Table 19 in terms of their mineralogical and microfabric properties.

10.2 Classification of Volcanic Saprolitic and Residual Soils

A classification of various soil types formed from volcanic and granitic rocks is given in Table 20, together with a summary of their structural and mineralogical properties, in accordance with the classification scheme proposed by Wesley & Irfan (1996). The soils of both granitic and volcanic origin fall into Group A, as structural (both micro and macro-structure) influences are dominant in controlling their behaviour. Thin layers or lenses of Group C soils rich in sesquioxides, may also form near ground surfaces, particularly in poorly drained areas. The formation of the Group (C_c) soils in Hong Kong is considered to be of minor occurrence in comparison to those developed in tropical regions : these soils are loosely referred to as lateritic or laterite.

In volcanic saprolitic soils, the kaolinite content may be more dominant than halloysite; they may also contain appreciably more mica, some chlorite and small amounts of swelling minerals of vermiculite, smectite and layered minerals of illite-smectite composition. Kaolinite may also be more dominant in volcanic soils if the original rock had been affected by hydrothermal and other alteration process prior to weathering.

Almost all soil zones including the highly weathered volcanic rock zone in Hong Kong would be classificed as 'ferruginous (sensu stricto) soil' under the classification scheme proposed by the Geological Society (1990), except perhaps the uppermost residual soil zone, which would be described as 'ferralitic (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 Irfan (1996a, b).

A large number of these weathering indices are derived from the results of chemical analyses. The selected chemical indices used to quantity the degree of weathering in volcanic rocks is given in Irfan (1996a). A number of petrographic indices were also determined from the results of the modal analysis, such as the percentages of altered and unaltered minerals, the micropetrographic index (Ip) following Irfan & Dearman (1978).

As the physical and mechanical properties of the volcanic rocks studied were not available, the indices derived from these properties were not determined. Also no attempt was made to classify the weathered volcanic rocks in terms of their dry density, void ratio, Schmidt hammer values or SPT N values, similar to that done for the granites (Irfan, 1996b).

11.2 Chemical Indices

The chemical weathering indices calculated for the volcanic rocks are presented in Tables 21 to 24. The mobiles index (I_{mob}) proposed by Irfan (1996a) serves as an index of the degree of decomposition of the feldspar-bearing rocks, particularly in reasonably well-drained (leaching) conditions, such as those found in most hillsides and hilltops in Hong Kong. The silica-to-alumina (SA) ratio has also 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). Both indices are not considered to be suitable for weathering conditions which result in smectite or vermiculite minerals, especially for basic and ultrabasic rocks. These two indices and the others calculated from chemical analyses do not account for the physical and fabric changes occurring with progressive weathering. It is the fabric properties which influence the engineering properties most in weathered rocks (Massey et al, 1988; Irfan, 1996b, c).

The results in Tables 21 to 24 indicate that the weathering potential index (WPI), alumina-to-potassium-sodium (AKN) ratio, the loss-on-ignition (LOI) value and the mobiles index are generally good indicators of the degree of weathering of volcanic rocks. These indices appear to be more suitable for characterizing the weathered materials formed over a particular rock type at a particular weathering environment. The chemical composition of fresh volcanic rocks can vary significantly not only from formation to formation but also within the same formation. In addition to chemical variation in the original rock, the mineralogy and chemical composition of the weathered product are affected by the environment and history of weathering at each site as well as other alteration processes as discussed in Section 9. This is illustrated in Figure 16, which is a plot of silica-to-alumina ratio against mobiles index for the weathered coarse ash tuffs from Aberdeen and Sai Kung. Similarly, Figure 17 shows an almost linear relationship between WPI and I_{mob} for the coarse ash tuff from Aberdeen in contrast to a wide scatter of values shown in Figure 18 when the data from all rocks are included.

The alumina-to-calcium-sodium (ACN) ratio appears to be useful only for indexing the rock grades of weathering and not sensitive to chemical changes occurring in the soil grades. The lixiviation index (β) is not a good indicator of weathering even for the soil grades, which it was originally proposed for by Rocha Filho et al (1985).

11.3 Degree of Decomposition Index

The degree of decomposition index (Lumb, 1965) nor the modified degree of decomposition index (Irfan, 1988) were determined for volcanic rocks as these indices were considered inappropriate for fine-grained volcanic rocks, especially those with a high content of cryptocrystalline or microcrystalline feldspar and quartz. Also, as discussed by Irfan (1996b), the degree of decomposition 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.

11.4 Micropetrographic Indices

Petrographical methods using an optical microscope and good quality thin sections are very useful in studying weathering effects. Not only do they allow cheap and rapid mineral identification but also the microfabric properties of the materials can be studied and characterized for the whole range of the weathering spectrum.

The point counting technique described by Irfan and Dearman (1978) was employed to determine the modal compositions of the mineral constituents, voids and microcracks for the weathered coarse-grained crystal tuffs only. Because of the extremely fine-grained nature of the matrix minerals, no individual mineral determinations were made and these were lumped together as the 'fresh matrix' or 'altered matrix' minerals. The results of quantitative determinations are presented in Table 5. It was not possible to differentiate between various fine-grained alteration products and small pores in the more weathered specimens under the normal resolution of an optical microscope. The results are, however, still useful as an appropriate means of quantifying the observed fabric changes occurring in each material.

The technique was found inappropriate for fine ash tuffs and the coarse ash tuffs with a large cryptocrystalline mineral contents, especially when they were weathered beyond the slightly decomposed grade. Also, general iron-staining or cementation of the fabric in moderately and more intensely decomposed volcanic rocks made the identification of mineral constituents very difficult.

12. CONCLUSIONS

Although chemical weathering has been the dominant process in profile development and soil formation in volcanic rocks in Hong Kong, cataclasis and shearing by tectonic processes and granite intrusions and the associated hydrothermal alteration have also been important. The general weathering profile in lithologically uniform volcanic rocks is similar to that of granitoid rocks, although the soil zones are generally thinner and the transition from 'all soil layer' to 'all rock layer' is generally more gradual and less distinct.

The recent classification scheme proposed by Wesley & Irfan (1996), which groups the soils on the basis of their mineralogical and structural characteristics, appears to be suitable for classifying the saprolitic and residual soils of volcanic rock origin.

The six-fold material weathering grade scheme, based on that adopted by Geotechnical Engineering Office (1988) but with further subdivisions and refinements that are proposed here can be used to describe and classify the weathered volcanic rock materials encountered within each broad soil group or rock mass zone.

A large number of mechanical, physical, chemical and petrographical indices are proposed to quantify the degree of weathering and weathered rock fabrics and some of these have been used to relate and indirectly determine engineering properties of weathered rocks. Only the chemical and petrographical indices have been determined for weathered volcanic rocks due to lack of data on physical and mechanical properties of the rocks studied here. Most proposed chemical indices, in particular the mobiles index, the weathering potential index and the alumina-to potassium-ratio, have been found to be good indicators of the degree of chemical weathering in a particular volcanic rock type, but direct comparison of index values at a particular weathering grade is not generally possible even for the same rock occurring in different formations. This is due to variations in the chemical composition and mineralogy of the weathering products arising from variations in the fresh rock and the environment and history of weathering at each site. The micropetrographic indices are only appropriate for the coarse-grained crystal tuffs due to the difficulty in recognising various fine mineral and fabric components under the microscope in fine-grained rocks, particularly those with vitrified and cryptocrystalline textures.

Although only the mineralogy and fabric properties of the fine and coarse ash tuffs were studied in detail, the results of the study and the general mineralogy and fabric characteristics observed in these rocks are considered to apply to other volcanic rocks in the Territory, except perhaps the more basic types.

In spite of great variation in their mineralogy and chemical composition and textures, the volcanic rocks show many similar mineralogy and fabric characteristics in the way they weather. However, significant differences can also occur, even in the same rock, if the rock has been affected by metamorphism and hydrothermal or other alteration processes prior to weathering. The unweathered rock may contain small amounts of secondary alteration products, mostly micaceous minerals, but also in some cases, kaolinite, calcite, chlorite and vermiculite. These secondary minerals are attributed to effects of epigenetic processes during volcanism and solidification, as well as the effects of contact metamorphism and hydrothermal alteration by the intruding magmas. Variations in the present day weathering and topographical environment can also lead to significant differences in void characteristics and clay mineralogy of the soils formed from the same rock at different locations.

In general, similar to granites, halloysite tends to form first, mainly from the decomposition of feldspars, unless the rock has been affected by other alteration processes, in which case, kaolinite is dominant, in the early stages of weathering. Halloysite becomes the dominant clay mineral with some muscovite/illite in the intermediate stages of weathering, which is then replaced by kaolinite in the near-surface saprolitic and residual soils. Small amounts of gibbsite may also be present in near-surface residual soils of volcanic rock origin.

Similar to granites, alkali feldspars in the tuffs are generally affected by weathering, initially by solution, much later than plagioclases, usually in the completely decomposed grade. Alteration may commence earlier in the highly decomposed grade in some tuffs. The tuffs underlying gentle hillslope and hilltop environments, where leaching of cations by groundwater occurs actively, show widespread solution type weathering of both the alkali feldspars and the fine-grained matrix with advanced honeycomb fabric development. Solution weathering seems to be more common in the coarse ash crystal tuffs than the fine ash tuffs.

The kaolin veins of both weathering and hydrothermal or mixed origin are common in the saprolitic soil zone. Those of hydrothermal origin, as well as the weathered rock itself, may contain some smectite minerals.

The presence of halloysite and sesquioxide minerals and the specific microstructure developed in the soil grades, require that special precautions are taken in the preparation of volcanic soil specimens for conventional laboratory testing and in the interpretation of the test results as discussed by Irfan (1996b, c).

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LIST OF TABLES

Table 1 - Comparison of Various Engineering and Geological Schemes Proposed for Classifying Weathering Profile in Igneous and Volcanic Rocks (after Irfan, 1996b)

<table>
<tr><th>Description of States of Weathering of Rock Mass</th><th colspan="2">BSI (1981)[1]
All Rocks</th><th colspan="2">GCO (1988)
Corestone-bearing Igneous Rocks</th><th colspan="2">Geological Society of London (1990)
All Rocks</th><th>Geological Society of London (1995)[2]
Heterogeneous Masses</th></tr>
<tr><td></td><td colspan="2">Soil</td><td colspan="2"></td><td colspan="2">Humus</td><td></td></tr>
<tr><td>All rock material converted to soil : mass structure and material fabric destroyed.
Significant change in volume</td><td>VI</td><td>Residual Soil</td><td>Residual Soil</td><td>RS</td><td rowspan="4">Residual Soil</td><td>VI</td><td rowspan="2">Zone 6
100%
GIV to VI</td></tr>
<tr><td rowspan="2">All rock material decomposed and/or disintegrated to soil.
Original mass structure still largely intact</td><td rowspan="2">V</td><td rowspan="2">Completely Weathered</td><td rowspan="3">(Saprolite)</td><td rowspan="3">PW
0/30
(< 30% Rock)</td><td rowspan="2">V</td></tr>
<tr></tr>
<tr><td rowspan="2">More than 50% of rock material decomposed and/or disintegrated to soil.
Fresh/discoloured rock present as discontinuous framework or corestones</td><td rowspan="2">IV</td><td rowspan="2">Highly Weathered</td><td rowspan="2">IV</td><td>Zone 5
<30%
GI - III</td></tr>
<tr><td rowspan="5">Partially Weathered Rock</td><td>PW
30/50</td><td>Zone 4
30-50%
GI - III</td></tr>
<tr><td rowspan="2">Less than 50% of rock material decomposed and/or disintegrated to soil.
Fresh/discoloured rock present as continuous framework or corestones</td><td rowspan="2">III</td><td rowspan="2">Moderately Weathered</td><td>PW
50/90</td><td rowspan="3">Weathered Bedrock</td><td rowspan="2">III</td><td>Zone 3
50-90%
GI to III</td></tr>
<tr><td rowspan="2">PW
90/100</td><td>Zone 2
>90%
GI - III</td></tr>
<tr><td>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</td><td>II</td><td>Slightly Weathered</td><td>II</td><td rowspan="2">Zone 1
100%
GI - III</td></tr>
<tr><td>No visible sign of rock material weathering, perhaps slight staining of major discontinuity surfaces</td><td>I</td><td>Fresh</td><td>Unweathered Rock</td><td>UW</td><td>Unweathered Bedrock</td><td>I</td></tr>
<tr><td colspan="8">Notes : 1. Scales of weathering grades of rock mass. Grades do not necessarily occur in the sequence indicated.
2. GI - GVI : Material weathering grades. GI to III are assumed to be rock and GIV to VI soil; soil is defined as weathered material which can be broken by hand.</td></tr>
</table>

Table 2 - Chemical Composition of Some Fine Ash and Coarse Ash Tuffs in Hong Kong

Rock Type	Formation	Locality	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	H_2O^+	H_2O^-	P_2O_5
Fine Ash Tuff	High Island	High Island (HK6003)	76.14	0.10	12.82	0.47	1.01	0.08	0.03	0.68	3.16	5.27	0.06	0.12	0.01
Fine Ash Tuff	Silverstrand	Kohima Site (HK6475)	75.21	0.16	13.01	0.42	1.24	0.07	0.16	0.69	3.04	4.94	0.88	0.14	0.03
Fine Ash Tuff	Ap Lei Chau	Junk Bay (HK5881)	67.17	0.39	15.72	1.37	2.56	0.13	0.49	1.72	2.89	5.92	1.22	0.16	0.14
Fine Ash Tuff	Ap Lei Chau	Junk Bay (HK6832)	70.47	0.42	14.35	0.67	2.53	0.12	0.50	2.26	3.15	4.08	0.95	0.08	0.10
Eutaxite	Ap Lei Chau	Ap Tsai, Junk Bay	67.79	0.41	15.58	3.45[1]	-	0.13	0.54	1.64	3.30	5.67	0.99	-	0.14
Coarse Ash Tuff	Tai Mo Shan	Wong Mo Ying (HK6608)	71.46	0.03	13.12	1.22	1.21	0.06	0.46	1.97	2.99	4.60	1.29	0.15	0.08
Coarse Ash Tuff	Tai Mo Shan	Tai Mo Shan (HK228)	68.96	0.60	13.89	1.44	2.92	0.09	1.32	2.93	1.69	4.92	1.40	0.14	0.14
Coarse Ash Tuff	Tai Mo Shan	Aberdeen	73.80	0.26	13.00	2.04[1]	-	0.07	0.35	1.81	2.74	4.56	0.95	-	0.07

Notes : 1. As combined Fe content.
2. Chemical analysis results are compiled from Geological Survey Memoirs published by GEO and this report.

Table 3 - Mineralogical Composition of 'Fresh' Volcanic Rocks (Based on Chemical Analysis and XRD)

Rock Type	Locality	Sample No.	Weight %							
			Quartz	K-Feldspar	Plagioclase	Kaolin Minerals	Micas	Iron oxides	Others	Total[1]
Fine Ash Tuff	Ap Tsai,	ATW1	46	19	24	-	tr	2	-	91
Fine Ash Tuff (Eutaxitic)	Tseung Kwan O	ATW2	28	22	30	11	tr	4	-	95
Fine Ash Tuff	Tseung Kwan O	TK01	32	18	24	8	tr	4	tr(C)	86
Coarse Ash Tuff	Sai Kung	SK7	30	18	24	15	tr	3	tr(C)	90
Coarse Ash Tuff	Aberdeen	IR1	39	21	33	-	1	-	5(C,V)	99
Coarse Ash Tuff	Yuen Long	YL1	38	4	30	-	10	4	-	86

Notes : 1. The sources of error are probably due to the presence of non-quantified minerals, such as mica, chlorite, carbonates, titanium oxides as well as calculation errors due to the stoichiometries assumed. C Chlorite; V Vermiculite

Table 4 - Composition of 'Fresh' Volcanic Rocks Determined from Modal Analysis

Rock Type	Locality	Sample No.	Description	Large Crystals (>0.5 mm)						Matrix Minerals		Total	
				Feldspars Fresh %	Feldspars Altered %	Quartz %	Biotite %	Altered Biotite %	Other %	Fresh Matrix %	Altered Matrix %	Crystal %	Matrix %
Fine Ash Tuff Eutaxitic	Ap Tsai, Tseung Kwan O	ATW1	Fresh	14.6	2.2	4.4	0.0	0.4	0.8	73.1	4.5	22.4	77.6
		ATW2	Fresher core	16.4	4.7	1.3	0.0	0.6	1.2	70.5	5.3	24.2	75.8
Fine Ash Tuff	Tseung Kwan O	TK01	Fresher core	13.7	4.5	0.5	0.0	1.4	1.4	69.8	9.7	21.5	79.5
Coarse Ash Tuff	Sai Kung	SK7	Fresher core of a corestone	17.4	12.3	4.2	0.0	1.9	0.9	59.0	4.3	36.7	63.3
Coarse Ash Tuff	Aberdeen	IR1	Fresher core of a corestone	28.5	3.8	14.8	0.4	5.0	0.1	44.4	2.9	52.7	47.3

Table 5 - Results of Modal Mineralogy and Quantitative Microfabric Determination, Weathered Coarse Ash Tuff, Aberdeen

Description	Sample No.	Large Crystals (%)					Matrix Minerals (%)		Others	Microcracks and Pores	Total	
		Fresh Feldspars (Plagioclase)	Altered Feldspars	Quartz	Biotite	Altered Biotite	Fresh	Altered			Fresh Minerals	Altered Minerals
(Fresh Tuff)	-	32.2(17.3)	-	14.8	5.4	-	47.4	-	0.1	0.0	100	-
Slightly Decomposed	IR1	28.5(13.6)	3.8	14.8	0.4	5.0	44.4	2.9	0.1	0.1	88.1	11.8
Moderately Decomposed	IR2	19.5(9.3)	9.0	18.9	1.0	3.2	34.3	12.7	0.0	1.3	73.7	24.9
Highly Decomposed	IR4	11.9(4.1)	7.8[1]	11.8	0.0	5.5	11.2	28.6[1]	1.1[3]	22.0[1]	34.9	43.0
Completely Decomposed	IR5	10.4(0.0)	12.2[2]	11.1	0.0	9.1	8.1	36.6[1]	0.2	12.2[1]	29.6	58.1
Residual (Transition) Soil	IR6	1.6(0.0)	(Note 2)	13.5	0.0	(Note 2)	4.7	64.5[2]	0.0	15.6[1]	19.8	64.5

Notes : (Fresh Tuff) composition recalculated from slightly decomposed tuff sample IR1, some chlorite is also present.

1. Approximate value, percentage of pores could be higher. Differentiation between minute altered areas and pores is not possible under the normal resolution power of microscope.
2. Included together as "altered matrix".
3. Mainly iron-oxide minerals.

Table 6 - Results of Chemical Analysis, Coarse Ash Tuff, Aberdeen

Description		Sample No.	Weight, %												
			SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	SO_3	LOI	Total
Slightly	(slightly discoloured)	IR1	73.80	0.26	13.00	2.34	0.07	0.35	1.81	2.74	4.58	0.07	0.00	0.95	99.67
Decomposed	(highly discoloured)	IR7+	72.40	0.27	14.20	2.39	0.04	0.47	1.19	2.60	5.23	0.07	0.01	0.97	99.84
Moderately Decomposed		IR2	72.70	0.27	13.70	2.32	0.04	0.32	1.21	2.42	5.20	0.07	0.00	0.99	99.24
		IR8+	72.60	0.29	14.40	2.44	0.30	0.44	0.26	0.88	5.79	0.06	0.01	2.17	99.64
Highly Decomposed		IR4	71.00	0.28	14.80	2.38	0.07	0.30	0.23	0.71	5.20	0.04	0.00	3.28	98.29
		IR9+	71.00	0.28	15.50	2.51	0.05	0.42	0.05	0.30	5.67	0.05	0.01	3.58	99.42
Completely Decomposed		IR52	72.10	0.27	14.30	2.48	0.08	0.20	0.06	0.11	3.86	0.04	0.00	7.40	100.90
		IR53	71.80	0.28	15.10	2.12	0.02	0.15	0.06	0.10	3.74	0.05	0.00	4.64	98.06
		IR54+	71.80	0.25	16.30	2.16	0.03	0.24	0.01	0.11	3.64	0.02	0.01	5.00	99.57
Completely Decomposed		IR34	70.50	0.29	16.30	2.54	0.02	0.18	0.05	0.07	2.11	0.03	0.00	6.25	98.33
		IR35	71.20	0.29	16.30	2.46	0.02	0.16	0.05	0.07	2.22	0.03	0.00	6.15	98.95
		IR36+	71.10	0.28	17.00	2.35	0.01	0.15	0.02	0.07	2.11	0.03	0.02	6.21	99.35
Transition Soil		IR61	69.00	0.32	17.90	3.32	0.02	0.17	0.05	0.03	0.53	0.02	0.00	7.80	99.16
		IR62	70.30	0.34	17.20	2.98	0.02	0.16	0.05	0.03	0.52	0.02	0.00	7.40	99.02
		IR63+	69.50	0.29	18.30	3.30	0.01	0.19	0.01	0.08	0.51	0.01	0.04	7.27	99.51

Notes : + Analyses carried out by Analabs (Australia); all other analyses carried out by Amdel (Australia)

Table 7 - Results of Chemical Analysis, Coarse Ash Tuffs, Sai Kung and Yuen Long

Description	Sample No.	Weight, %													
		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	CO_2	SO_3	LOI	Total
Sai Kung															
Slightly Decomposed (Lava)	SK6	67.95	0.39	15.95	3.16	0.12	0.54	1.57	3.35	5.75	0.14	0.09	0.01	1.00	100.01
Slightly Decomposed (fresh core)	SK7	67.17	0.39	14.79	3.35	0.08	0.92	2.15	2.89	4.52	0.14	1.45	0.02	1.49	99.37
Moderately Decomposed	SK5	67.56	0.47	16.37	3.89	0.04	0.93	0.08	1.61	4.45	0.09	0.13	0.01	4.14	99.81
Highly Decomposed	SK4	65.71	0.57	18.86	4.08	0.03	0.59	0.01	0.13	2.77	0.08	0.20	0.01	7.25	100.29
Completely Decomposed	SK2	66.97	0.55	18.27	4.15	0.04	0.64	0.01	0.16	2.64	0.04	0.24	0.01	6.38	100.10
Completely Decomposed	SK3	65.46	0.56	18.94	4.21	0.03	0.60	0.01	0.11	2.49	0.10	0.08	0.01	8.06	100.67
Residual Soil	SK1	54.51	0.50	19.47	4.44	0.03	0.55	0.01	0.07	1.64	0.05	0.63	0.02	18.53	100.45
Yuen Long															
Slightly Decomposed (fresh core)	YL1	69.18	0.50	14.30	4.33	0.11	1.55	2.69	3.61	2.66	0.11	0.73	0.00	0.73	99.77
Highly Decomposed	YL6	70.57	0.52	14.08	3.52	0.06	0.84	2.58	1.99	4.19	0.16	1.45	0.00	1.45	99.96
Highly Decomposed	YL3	68.25	0.54	14.50	4.69	0.09	1.10	3.02	2.00	3.45	0.17	1.90	0.00	1.90	99.71
Completely Decomposed	YL5	67.85	0.59	15.82	4.81	0.11	1.24	1.92	0.24	3.62	0.14	4.04	0.00	4.04	100.38
Completely Decomposed (deformed)	YL4	67.99	0.60	15.33	4.97	0.32	1.03	1.29	0.41	3.89	0.13	3.82	0.00	3.82	99.78

Table 8 - Results of Chemical Analysis, Fine Ash Tuff and Eutaxite, Tseung Kwan O

Description		Sample No.	Weight, %													
			SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	CO_2	SO_3	LOI	Total
Ap Tsai Headland																
Fresh Fine Ash Tuff		ATW1	74.44	0.18	13.21	1.84	0.07	0.28	0.98	2.82	4.95	0.05	0.29	0.01	0.50	99.62
'Fresh' Eutaxitic Fine Ash Tuff		ATW3F	67.79	0.41	15.58	3.45	0.13	0.54	1.64	3.30	5.67	0.14	0.01	0.01	0.99	99.66
Slighly	(slightly discoloured)	ATW2	67.99	0.42	16.15	3.52	0.16	0.58	1.64	3.62	5.57	0.16	0.16	0.01	0.83	100.81
Decomposed	(moderately discoloured)	ATW3	67.28	0.38	15.68	3.74	0.10	0.46	1.05	3.16	5.99	0.12	0.08	0.01	1.64	99.65
Moderately Decomposed		ATW3W	66.76	0.35	15.78	4.02	0.06	0.37	0.45	3.02	6.30	0.09	0.14	0.01	2.29	99.64
Highly Decomposed		ATW4	63.50	0.37	16.14	3.82	0.06	0.28	0.03	0.18	3.35	0.06	0.39	0.01	11.64	99.83
Highly Decomposed	(altered)	ATW5	69.73	0.37	13.99	2.89	0.07	0.36	0.03	0.29	4.75	0.04	0.36	0.01	7.10	99.99
Completely Decomposed		ATW6	63.57	0.46	18.53	3.92	0.03	0.28	0.02	0.16	1.61	0.05	0.63	0.01	10.13	99.40
Tseung Kwan O																
Fresh Fine Ash Tuff		TK01	63.85	0.63	17.14	4.18	0.13	1.00	4.08	2.88	4.69	0.19	0.30	0.01	1.39	100.47
Slightly	(fresh core)	TK02F	64.65	0.63	16.95	4.08	0.11	0.99	3.17	3.08	4.28	0.18	0.18	0.01	1.52	99.83
Decomposed	(stained rim)	TK02W	62.14	0.76	17.75	4.52	0.14	0.97	1.80	1.12	5.43	0.08	0.10	0.01	5.25	100.07
	Mean	TK02	63.40	0.70	17.35	4.30	0.13	0.98	2.48	2.10	4.86	0.13	0.14	0.01	3.39	99.97
Moderately Decomposed		TK03	61.41	0.70	17.85	3.84	0.09	0.83	1.45	1.65	5.82	0.15	0.01	0.01	6.10	99.91
Highly Decomposed		TK05	60.54	1.02	20.09	6.55	0.11	0.86	0.09	0.15	3.04	0.05	0.01	0.01	7.70	100.22
Highly Decomposed	(altered)	TK04	53.24	0.84	21.62	5.49	0.10	1.00	0.06	0.13	2.57	0.06	0.05	0.01	15.36	100.53
Fine Ash Tuff (quartz crystal rich):																
Completely Decomposed		TK06	68.66	0.36	18.11	2.96	0.03	0.25	0.01	0.19	3.49	0.04	0.04	0.01	5.77	99.92
Completely Decomposed		TK07	62.95	0.38	20.97	4.44	0.04	0.37	0.01	0.36	2.39	0.05	0.43	0.02	7.80	100.21
Residual Soil		TK08	55.46	1.09	23.22	8.22	0.06	0.41	0.01	0.14	2.39	0.08	0.32	0.02	9.08	100.52

Table 9 - Results of Semi-quantitative Bulk XRD Analysis, Coarse Ash Tuff, Aberdeen

Description	Sample No.	Feldspars	Quartz	Biotite	Kaolin minerals	Muscovite illite	Chlor. vermic.	Mixed-layer	Iron oxides
Slightly Decomposed	IR1	CD (F'F)	CD	Tr-A	-	-	Tr (C, V)	-	-
Moderately Decomposed	IR2	SD (F'F)	D	Tr-A	Tr	-	Tr (V)	-	-
	IR8+	SD	D	Tr	Tr	Tr	Tr (C-V)	Tr (I-S)	Tr
Highly Decomposed	IR4	SD (F'F)	D	Tr	A	Tr	-	-	-
	IR9+	SD -A	D	-	A-SD	A	Tr (C-V)	Tr (I-S)	Tr
Completely Decomposed	IR52	A-SD (F')	D	-	SD	A	Tr (C-V)	-	Tr
	IR53	SD (F')	D	-	A	Tr-A	Tr (C-V)	-	-
	IR54+	A	D	-	SD	Tr-A	Tr (C-V)	Tr	Tr
Completely Decomposed	IR34	A (F')	D	-	SD	A	Tr (C-V)	-	Tr (H?)
	IR35	Tr-A (F')	D	-	SD	Tr-A	-	-	Tr
	IR36+	Tr-A	D	-	SD	Tr-A	-		Tr
Residual (Transition)	IR61	-	D	-	SD	Tr	Tr (C-V)	-	Tr-A (G)
Soil	IR62	-	D	-	SD	Tr	Tr (C-V)	-	Tr-A (G)
	IR63+	-	D	-	D	Tr-A	-		Tr

Notes : F, Plagioclase; F', Alkali feldspar; (F'F), Both feldspars present, first more abundant; C-V, Interlayered chlorite and vermiculite; S, Smectite; G, Goethite; H, Hematite; I-S, Mixed clay mineral of possible illite-smectite composition;

Dominance scale;

D, Dominant. Used for the component apparently most abundant regardless of its probable percentage level.

CD, Co-dominant. Used for two (or more) predominating components, both or all of which are judged to be present in roughly equal portions.

SD, Sub-dominant. The next most abundant component(s) with percentage level <20%.

A, Accessory. Components judged to be between 5% and 20%.

Tr, Trace. Components judged to be below about 5%.

+, Results by Analabs (Australia), all other analysis results by Amdel (Australia).

Table 10 - Results of Semi-quantitative Bulk XRD Analysis, Coarse Ash Tuffs, Sai Kung and Yuen Long

Description	Sample No.	Feldspars		Quartz	Muscovite	Kaolin Minerals	Others
		K-feldspar	Plagioclase				
Sai Kung							
Slightly Decomposed (Lava)	SK6	+++	+++	+++	tr	+	tr(C)
Slightly Decomposed (fresh core)	SK7	++	++	++++	tr	+	tr(C)
Moderately Decomposed	SK5	++	++	++++	tr	+	+(C)
Highly Decomposed	SK4	+	tr	++++	+	+++	
Completely Decomposed	SK2	tr	ND	++++	+	+++	
Completely Decomposed	SK3	tr	ND	++++	+	+++	
Residual Soil	SK1	ND	ND	++++	ND	+++	
Yuen Long							
Slightly Decomposed (fresh core)	YL1	++	+++	++++	+++	ND	
Highly Decomposed	YL6	++	++	++++	+	+	
Highly Decomposed	YL3	++	++	++++	+	+	
Completely Decomposed	YL5	++	tr	++++	++	++	tr(C)
Completely Decomposed (deformed)	YL4	++	tr	++++	++	++	

Notes : Small amount of (less than 5%) iron-oxides and hydroxides may also be present. C Chlorite; ND Not detected; N/A Not analysed.
Dominance Scales : ++++ Dominant (>50%); +++ Major (20-50%); ++ Minor (10-20%); + Present (5-10%); Tr Trace (0-5%).

Table 11 - Results of Semi-quantitative Bulk XRD Analysis, Fine Ash Tuffs and Eutaxite, Tseung Kwan O

Description	Sample No.	Feldspars		Quartz	Micas	Kaolin Minerals	Others[1]
		K-feldspar	Plagioclase				
Ap Tsai Headland							
Fresh Fine Ash Tuff	ATW1	++	++	++++	tr	tr	tr(C)
Fresh Eutaxitic Fine Ash Tuff	ATW3F	++	++	++++	tr	tr	tr(C)
Slightly (slightly discoloured)	ATW2	++	++	++++	tr	+	
Decomposed (moderately discoloured)	ATW3	++	++	+++	tr	+	
Moderately Decomposed	ATW3W	++	++	++++	tr	tr	
Highly Decomposed	ATW4	+	tr	++++	tr	++	
Highly Decomposed (altered)	ATW5	++	tr	++++	tr	++	
Completely Decomposed	ATW6	+	tr	++++	tr	+++	
Tseung Kwan O							
Fresh Fine Ash Tuff	TK01	+++	+++	+++	tr	+	+(C)
Slightly (fresh core)	TK02F	+++	+++	+++	tr	+	+(C)
Decomposed (stained rim)	TK02W	+++	+	++++	tr	+	+(C)
Moderately Decomposed	TK03	+++	+	++++	tr	+	+(C)
Highly Decomposed	TK05	++	?	++++	tr	+	+(C)
Highly Decomposed (altered)	TK04	++	tr	++++	+	+++	+(C)
Fine Ash Tuff quartz crystal rich)							
Completely Decomposed	TK06	++	ND	++++	+	++	
Completely Decomposed	TK07	+	ND	++++	+	+++	
Residual Soil	TK08	+	ND	+++	tr	+++	

Notes : 1. Small amounts (less than 5%) iron-oxides and hydroxides are also present. C Chlorite. See Table 10 for dominance scales.

Table 12 - Results of Semi-quantitative Clay Mineralogy Determined from XRD, Coarse Ash Tuff, Aberdeen

Description	Sample No.	Kaolin Minerals	Muscovite Illite	Chlor. Vermic.	Mixed Layer	Iron-oxides	Kaolinite Halloysite Ratio
Slightly (slightly discoloured	IR1	-	(A)**	Tr-A (C,V)	-	-	0:0
Decomposed (moderately discoloured)	IR7$^+$	Tr	Tr	Tr (C-V)	-	Tr	ND
Moderately Decomposed	IR2	A	(A-SD)***	A-SD (V)	-	-	100:0
	IR8$^+$	A	Tr	Tr (C-V)	Tr (I-S)	Tr	ND
Highly Decomposed	IR4	D	(SD)**	-	-	-	45:55
	IR9$^+$	D	SD	Tr (C-V)	-	Tr	ND
Completely Decomposed	IR52	D	Tr	-	-	-	15:85*
	IR53	D	Tr	-	-	-	15:85*
	IR54$^+$	D	A	Tr (C-V)	Tr (I-S)	-	ND
Completely Decomposed	IR34	D	A	-	-	-	10:90*
	IR35	D	A	-	-	Tr (H) ?	10:90*
	IR36$^+$	D	Tr	Tr (C-V)	-	-	ND
Residual (Transition)	IR61	D	Tr	-	-	Tr-A (G)	85:15
Soil	IR62	D	A	-	-	Tr-A (G)	85:15
	IR63$^+$	D	Tr	Tr (C-V)	Tr (I-S)	-	ND

Notes : See Table 9 for explanation. Kaolinite : Halloysite ratio determined by Churchman (1974) method. * Hydrated halloysite detected.
** Reported as biotite.

Table 13 - Results of Semi-quantitative Clay Mineralogy Determined from XRD, Coarse Ash Tuffs, Sai Kung and Yuen Long

Description	Sample No.	Kaolin Minerals		Micas	Others
		Kaolinite	Halloysite		
<u>Sai Kung</u>					
Slightly Decomposed (fresh core)	SK7	N/A	N/A	N/A	N/A
Moderately Decomposed	SK5	+	ND	+++	+(C)
Highly Decomposed	SK4	+++	?tr	++	
Completely Decomposed	SK2	+++	ND	++	
Completely Decomposed	SK3	+++	ND	++	
Residual Soil	SK1	++++	ND	tr	+(V), ++(HM)
<u>Yuen Long</u>					
Slightly Decomposed (fresh core)	YL1	N/A	N/A	N/A	N/A
Highly Decomposed	YL6	+++	ND	+++	
Highly Decomposed	YL3	+++	ND	+++	
Completely Decomposed	YL5	++++	+	++	
Completely Decomposed (deformed)	YL4	++++	ND	++	

Notes: See Table 10 for dominance scales.. HM Hydrobiotite; C Chlorite; V Vermiculite.

Table 14 - Results of Semi-quantitative Clay Mineralogy Determined from XRD, Fine Ash Tuff and Eutaxite, Tseung Kwan O

Description	Sample No.	Kaolin Minerals		Micas	Others
		Kaolinite	Halloysite		
Ap Tsai Headland :					
Fresh Fine Ash Tuff	ATW1	N/A	N/A	N/A	N/A
'Fresh' Eutaxitic Fine Ash Tuff	ATW3F	N/A	N/A	N/A	N/A
Slightly (slightly discoloured)	ATW2	N/A	N/A	N/A	N/A
Decomposed (moderately discoloured)	ATW3	+++	ND	++	
Moderately Decomposed	ATW3W	N/A	N/A	N/A	N/A
Highly Decomposed	ATW4	+++	++	+	
Highly Decomposed (altered)	ATW5	+++	+	++	
Completely Decomposed	ATW6	++	++	+	
Tseung Kwan O					
Fresh Fine Ash Tuff	TK01	N/A	N/A	N/A	N/A
Slightly (fresh core)	TK02F	N/A	N/A	N/A	N/A
Decomposed (stained rim)	TK02W	+++	?tr	++	++(C)
Moderately Decomposed	TK03	+++	?tr	++	?(C)
Highly Decomposed	TK05	N/A	N/A	N/A	N/A
Highly Decomposed (altered)	TK04	+++	?tr	++	+(C)
Fine Ash Tuff (quartz crystal rich)					
Completely Decomposed	TK06	+++	++	+	
Completely Decomposed	TK07	++++	ND	++	+(V)
Residual Soil	TK08	++++	ND	++	tr(V)

Notes : See Table 10 for dominance scales. C Chlorite; V Vermiculite.

Table 15 - Results of Quantitative Bulk Norm Mineralogy, Coarse Ash Tuff, Aberdeen (Based on Chemical Analysis)

Sample No.	Feldspars		Quartz	Micas	Kaolin Minerals	Iron-oxides	Others
	K-feldspar	Plagioclase					
IR1	21	33	39	1(B)	-	-	tr(V), 5(C)
IR2	27	26	34	7(B)	4	-	tr(V)
IR4	27	7	38	7(B)	18	-	-
IR52/53	11	0	50	17(M)	17	-	-
IR34/35	8	-	48	7(M)	31	3(G)	-
IR61/62	-	-	49	5(M)	40	-	-

Notes : G Goethite; H Hematite; V Vermiculite; B Biotite; M Muscovite/hydrous mica/illite

Table 16 - Results of Quantitative Bulk Norm Mineralogy, Coarse Ash Tuffs, Sai Kung and Yuen Long (Based on Chemical Analysis)

Description	Sample No.	Feldspars		Quartz	Micas	Kaolin Minerals	Iron-oxides	Others
		K-feldspar	Plagioclase					
Sai Kung								
Slightly Decomposed (lava)	SK6	23	28	31	-	6	3	<5(C)
Slightly Decomposed (fresh core)	SK7	18	24	30	tr	15	3	tr(C)
Moderately Decomposed	SK5	13	14	36	7	18	2(G)	5(C)
Highly Decomposed	SK4	11	1	38	<5	43	4	
Completely Decomposed	SK2	10	1	38	<5	46	4	
Completely Decomposed	SK3	10	1	38	<5	43	4	
Residual Soil	SK1	6	1	27	ND	49	5(G)	
Yuen Long								
Slightly Decomposed (fresh core)	YL1	4	30	38	10	N/A	4	
Highly Decomposed	YL6	15	17	42	3	11	4	
Highly Decomposed	YL3	8	17	38	9	12	5	
Completely Decomposed	YL5	9	2	42	8	27	5	
Completely Decomposed (deformed)	YL4	10	3	40	8	28	5	

Notes : G Goethite; C Chlorite

Table 17 - Results of Quantitative Bulk Norm Mineralogy, Fine Ash Tuff and Eutaxite, Tseung Kwan O (Based on Chemical Analysis)

Description	Sample No.	Feldspars		Quartz	Micas	Kaolin Minerals	Iron-oxides	Others
		K-feldspar	Plagioclase					
<u>Ap Tsai Headland</u>								
Fresh Fine Ash Tuff	ATW1	19	24	46	tr	N/A	2	
Fresh Eutaxitic Fine Ash Tuff	ATW3F	N/A	N/A	N/A	N/A	N/A	N/A	
Slightly (slightly discoloured)	ATW2	22	30	28	tr	11	4	
Decomposed (moderately discoloured)	ATW3	24	27	31	tr	8	4	
Moderately Decomposed	ATW3W	N/A	N/A	N/A	N/A	N/A	N/A	
Highly Decomposed	ATW4	13	2	36	tr	39	4	
Highly Decomposed (altered)	ATW5	19	2	46	tr	22	3	
Completely Decomposed	ATW6	6	1	36	tr	48	4	
<u>Tseung Kwan O</u>								
Fresh <u>Fine Ash Tuff</u>	TK01	18	24	32	tr	8	4	<5(C)
Slightly (fresh core)	TK02F	17	26	31	tr	10	4	<5(C)
Decomposed (stained rim)	TK02W	21	9	32	tr	20	5	<5(C)
Moderately Decomposed	TK03	23	14	28	tr	20	4(G)	<5(C)
Highly Decomposed	TK05	N/A	N/A	N/A	N/A	N/A	N/A	
Highly Decomposed (altered)	TK04	10	1	24	<5(C)	48	6(G)	<5(C)
<u>Fine Ash Tuff (quartz crystal rich)</u>								
Completely Decomposed	TK06	14	2	40	<5(C)	39	3	
Completely Decomposed	TK07	7	3	32	4	45	4	
Residual Soil	TK08	9	1	22	tr	56	9(G)	

Notes : C Chlorite; G Goethite.

Table 18 - Mineralogy of Kaolin Veins in Hong Kong (after Irfan & Woods, 1997)

Landslide Site	Rock Type	Description of Vein/Shear Zone Infilling	Mineral Composition	Reference
Island Rd Govn School, Aberdeen	Coarse ash crystal tuff (hydrothermally altered)	White clay vein	K*(D), I(Tr), G(Tr-A), S(A)	Irfan (1992)
		White clay vein	K*(D), I(Tr)	Irfan (1994)
		White clay vein	K(D), I(Tr-A)	
		Clay seam in shear zone	K*(SD), I(Tr-A), Q(D), F'(Tr) G(Tr-A)	
Tin Wan Hill Road, Aberdeen	Coarse ash crystal tuff (hydrothermally altered)	White clay vein	K(D), I(Tr)	Irfan (1992)
Siu Sai Wan, Chai Wan	Quartz deficient (hydrothermally altered) tuff	Vein infilling	K*(D), Q(SD), A(?)Tr	In-house test results
Shum Wan Road Aberdeen	Eutaxitic crystal vitric tuff	White clay in slip plane	K(D), I(Tr), Q(A-Tr)	In-house test results
		Clay coating	K(D), I(Tr), I/S(Tr), Q(Tr)	
		Brown clay infilling	K(D), Q(A-Tr), Todorokite	
		Joint clay	K(D), I(Tr), I/S(Tr), Q(A)	
Fei Tsui Road, Chai Wan	Crystal tuff and lapilli tuff (hydrothermally altered bedding shear zone)	White clay vein	K(D), I(Tr), Q(A)	In-house test results
		Brown clay (in heavily altered bedding shear zone)	K(D), I(Tr), V(A), Q(A)	
		Vein clay	K(D), I(Tr), Q(Tr)	

Notes :

K	- Kaolinite or kaolin minerals	G	- Goethite
*	- Halloysite present	A	- Allophane (?)
I	- Illite	Q	- Quartz
M	- Fine grained micaceous minerals	C-V	- Mixed chlorite-vermiculite mineral
S	- Smectite	F'	- Alkali feldspar

Dominance Scales for mineralogical composition : D (Dominant) - component most abundant. CD (Codominant) - two or more predominating components, both or all present in roughly equal proportions. SD (Subdominant) - the next most abundant component(s) with percentage level >20%. A (Accessory) - Component between 5% and 20%. Tr (Tr) - Component less than 5%. ? - Possibly present in trace amounts.

Table 19 - Classification of Material Weathering Grades of Volcanic Rocks in Terms of Petrological Change

Material weathering grade	Hand specimen	Fabric properties			Mineralogical composition[1]		
	Visual effects	Decomposition of crystals	matrix	Microfracturing/ pore development/ grain boundaries	Primary minerals	Secondary minerals	Relative strength
Fresh	Light to bluish grey to black. Varying proportions of quartz and feldspar crystals, sometimes vitric fragments or lapilli, in a very fine vitric (glassy) to finely recrystallized matrix. Weak to strong welding fabric or flow banding may be present. Texture and mineralogy may vary rapidly.	Feldspars may be slightly sericitised. Biotite usually partially/completely altered.	Small amounts of chlorite, calcite, kaolinite and vermiculite may be present.[2]	Rock fabric unfractured except in tectonically affected volcanic rocks. Indistinct resorbed crystal grain boundaries with devitrified/crystallised matrix.	P_f(SD-CD) K_f(SD-CD) Q(A-CD) B(Tr-A) M(Tr)	K[2](?-Tr) C[2](Tr) V(Tr) Ca[3](?-Tr) M[2](Tr)	Extremely strong (fine grained rock) to very strong (coarse grained rock)
Slightly Decomposed	(i) Slightly Discoloured: Less than 10% staining.	Fresh core: Similar to fresh rock. Stained rim: Plagioclases slightly decomposed.	Similar to fresh rock. Similar to fresh rock.	Rock fabric unfractured. Grain boundaries are tight but stained. Some minute solution pores/voids in feldspars and matrix.	P_f(SD-CD) K_f(SD-CD) Q(A-CD) B(?-Tr) M(Tr)	K[2](Tr) C,V(Tr) M[2](Tr) Ca(?) Int[4](?)	Extremely strong to very strong
	(ii) Moderately Discoloured: 10% to 50% staining.	Fresher core: Slight increase in decomposition of feldspars.		Few tight microcracks in larger grains.	Q(A-D) K_f(SD-CD) P_f(SD) B(Tr) M(Tr)	K[2](Tr) H(?-Tr) M[2,6](Tr-A) C,V(Tr) Ca(?) Int[4](?) G(Tr) S[2]	Very strong to strong
	(iii) Highly Discoloured: More than 50% staining. Fresher core may show light grey discoloration. Colour banding may be present. Feldspar crystals become progressively softer towards the joint surfaces. Concentric development of microfractures around the fresher core, particularly in coarse grained rocks.	Most plagioclases slightly to moderately decomposed to micaceous and kaolin minerals. In some rocks, only plagioclase crystals are affected. Biotite partially to wholly altered to mixture of chlorite, vermiculite, micaceous and iron-oxide minerals.	Matrix minerals may show slight decomposition and some solution effects.	Simple branched, stained, tight microcracks throughout the matrix. Cloudy or speckled areas in large feldspars and matrix are either locations of solution pits/voids or poorly crystalline kaolin minerals.			
Moderately Decomposed	Complete staining. One type of feldspars partially gritty throughout. Biotite dull greenish grey and soft. Rock material is fractured by an irregular network of tight to slightly open microcracks. Material strength significantly reduced. (Cannot be broken by hand, easily broken by hammer blows)	Most plagioclases highly decomposed. Alkali feldspars may only be slightly affected but highly microfractured.	Matrix minerals slightly decomposed and stained throughout.	Fabric fractured by complex-branched microcracks. Grain boundaries tight but stained. Some pore development in large feldspars, particularly alkali feldspars, and the matrix.	Q(A-D) K_f(SD) P_f(SD-A) B(?)	K[2,4](Tr-A) H(Tr) M[6](Tr-A) Int(Tr) C,V(Tr) G(Tr) H_e(Tr) S[2]	Moderately strong to weak

Table 19 - Classification of Material Weathering Grades of Volcanic Rocks in Terms of Petrological Change (cont'd)

	Hand specimen	Fabric properties			Mineralogical composition[1]		
Material weathering grade	Visual effects	Decomposition of crystals	matrix	Microfracturing/ pore development/ grain boundaries	Primary minerals	Secondary minerals	Relative strength
Highly Decomposed	Complete discoloration to light yellowish grey to yellowish brown. Extensively microfractured. Plagioclase crystals gritty to powdery, occasionally soft. Alkali feldspar crystals hard to gritty, highly microfractured. (Less weathered specimens can be broken by hand, more weathered specimens broken into a mixture of friable rock fragments and individual mineral grains.)	Most plagioclases completely decomposed to kaolin minerals; porous microfabrics may develop in some rocks. Alkali feldspars show initial stages of solution. More clayey fabrics or more intenser decomposition to kaolinite in rocks affected by hydrothermal alteration.	Matrix feldspars highly to completely decomposed.	Highly fractured by complex-branched slightly open microcracks. Porous matrix fabric may develop in well-drained areas.	Q(A-D) K_f(A) P_f(Tr-A)	H(A) $K^{2,4}$(Tr-A) M^6(Tr-A) C,V(?-Tr) G(Tr) H_c(?-Tr) Int(?)	Weak to very weak
Completely Decomposed	Yellowish grey to reddish brown, but may be mottled or pinkish or purplish grey if altered. Most feldspar crystals powdery to soft some gritty. Groundmass is gritty to soft. Volcanic rock fabric still preserved. (Can be crumbled into individual soil grains by finger pressure, usually slakes in water.) (Generally clayey sandy silts to sandy clayey silts in disturbed state.)	Plagioclases completely decomposed to halloysite kaolinite. Alkali feldspars show intense solution type weathering with advanced honeycomb fabric development in well-drained areas, elsewhere highly decomposed to kaolinite. Decomposed biotite may show expansion.	Matrix feldspars completely decomposed	Original rock fabric intact but highly microfractured. Grain boundaries mostly open. Generally denser clayey fabrics developed in fine-grained rocks and poorly-drained areas, fractured and porous fabric in coarse-grained rocks. However, clay mineralogy and microfabrics in feldspars and in the matrix may be very variable depending on intensity of weathering, alteration and leaching conditions. Cementation by iron-oxides may locally be intense, obliterating soil fabric.	Q(A-D) K_f(Tr-A) P_f(Tr-?)	H^5(Tr-CD) K(A-CD) M^6(Tr-A) G(Tr-A) C,V(Tr) H_c(?-Tr) Int(?)	Extremely weak to very dense to dense
(Transition Soil)	Reddish brown, but may be mottled yellowish grey. Soil shows partial volcanic rock fabric but no relict discontinuities.	Alkali feldspars highly to completely decomposed to kaolinite. Slight solution of quartz.		Original rock fabric partially lost.	Q(A-SD) K_f(Tr)	K(A-CD) H(Tr) M(Tr) C,V(Tr) H_c(Tr-?) G(Tr-A)	Very dense to dense

Table 19 - Classification of Material Weathering Grades of Volcanic Rocks in Terms of Petrological Change (cont'd)

Material weathering grade	Hand specimen	Fabric properties			Mineralogical composition[1]		
	Visual effects	Decomposition of crystals	matrix	Microfracturing/ pore development/ grain boundaries	Primary minerals	Secondary minerals	Relative strength
Residual Soil	Yellowish brown, yellowish grey when leached. Soil comprises sand-size quartz grains in a structureless clayey silt to silty clay matrix. Modules or Pods of cemented soil particles may be present. Locally, complete cementation may occur.	No feldspar present. Slight to noticeable solution of quartz.	Matrix completely destroyed.	No original rock fabric coating and cementation by iron-oxides and hydroxides may be locally intense. Microcracks much reduced, but secondary pores, cracks may be present due to desiccation, burrowing activity by animals, etc.	Q(A-SD)	K(D) H(Tr) G(A) V,C(Tr-?) M(Tr) Gi(Tr)	Dense (or very stiff if clayey) to loose (or stiff) (may be weakly cemented)

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

1. Dominance scales for mineralogical composition (excluding pore content): 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 be between 5% and 20%. Tr-Trace - Component judged to be less than 5%. ? - Possibly present in trace amounts. 2. Kaolinite, chlorite, vermiculite and muscovite may be present from alteration of feldspars and biotite. 3. Small amount of calcite may be present as a breakdown product of feldspar by hydrothermal process. 4. Poorly crystalline kaolinite may form through an amorphous alumina-silicate gel in early stages of weathering. 5. Kaolinite may be dominant if rock is intensely altered. 6 Fine-grained micaceous minerals (muscovite/hydrous mica/illite) of weathering origin. 7. 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 volcanic rocks.

Table 20 - Classification of Granitic and Volcanic Soils in Hong Kong (Irfan, 1996c)

Engineering mass weathering grade or Zone (based on BSI, 1981 and Irfan, 1996)		Residual soil group (Wesley & Irfan, 1996)	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). (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 (Local concentration of goethite/hematite in Group C(c)). Minor vermiculite/mica in volcanic soils[3].
(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) rock fabric decreasing upwards in weathering profile; very weak secondary bonding.	Quartz with kaolinite, some halloysite, minor goethite and illite/muscovite, occassional K-feldspar. Quartz content may be appreciably less in volcanics.
Saprolite	Completely Weathered	Group A(b)	Relict joints and other mass features and rock fabric preserved; dominantly composed of loose to dense material with very weak relict[5] bonding, and occasional less weathered rock (corestones).	Quartz[4] with kaolinite and halloysite[6], some partially decomposed K-feldspars, minor goethite and illite/muscovite[3]. (Local concentration of goethite/hematite may occur at some depth below ground surface).
		to		
		Group A(a)	Dominantly composed of dense to very dense material with weak relict bonding, and up to 10% less weathered rock (corestones), particularly in medium to coarse-grained granites and volcanics.	Quartz with halloysite and some kaolinite[6], and porous K-feldspar, minor illite/muscovite. Kaolinite may be more dominant than halloysite in volcanics.
	Highly weathered	Group A(a)	Up to 30% partially weathered rock fragments or continuum (especially in volcanics) in loose to very dense soil material.	Quartz and K-feldspars[7] with some halloysite, minor plagioclase, kaolinite, muscovite. Kaolinite may be more dominant than halloysite in volcanics; also appreciably more mica and some chlorite.
		to		
		Not applicable (should be described as partially weathered rock)	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).	

Notes : 1. Excluding less weathered corestones in soil. 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, or in volcanic soils affected by hydrothermal alteration. 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. More variable K-feldspar, plagiocase and quartz contents in volcanic rocks.

Table 21 - Chemical Weathering Indices, Weathered Coarse Ash Tuff, Aberdeen

Sample No.	Weathering Potential Index*	Weathering Product Index*	Silica to Alumina Ratio*	Alumina to Potassium Sodium Ratio	Alumina to Calcium Sodium Ratio	Lixiviation Index	Mobiles Index*	Loss on Ignition
IR1	5.38	89.54	9.63	1.78	0.74	0.10	0.00	0.95
IR7	5.12	88.43	8.65	1.81	0.79	0.18	0.05	0.97
IR2	4.63	88.82	9.01	1.80	0.79	0.13	0.07	0.99
IR8	-2.00	88.30	8.56	2.56	0.93	0.40	0.36	2.17
IR4	-7.30	87.84	8.14	2.50	0.94	0.30	0.43	3.28
IR9	-8.56	87.34	7.77	2.60	0.98	0.56	0.47	3.58
IR52/53/54	-19.01	88.77	8.04	3.96	0.99	0.32	0.66	5.68
IR34/35/36	-22.71	86.70	7.28	7.36	0.99	0.17	0.81	6.20
IR61/62/63	-29.64	85.37	6.64	31.42	1.00	0.04	0.94	7.49

Notes : * Calculated from molecular weights. Sample numbers are arranged in order of increased degree of weathering.

Table 22 - Chemical Weathering Indices, Weathered Coarse Ash Tuff, Sai Kung

Sample No.	Weathering Potential Index*	Weathering Product Index*	Silica to Alumina Ratio*	Alumina to Potassium Sodium Ratio	Alumina to Calcium Sodium Ratio	Lixiviation Index	Mobiles Index*	Loss on Ignition
SK7	5.02	86.74	7.71	2.00	0.75	0.18	0.00	1.50
SK5	-9.51	85.49	7.00	2.70	0.91	0.63	0.36	4.18
SK4	-26.23	83.40	5.91	6.50	0.99	0.30	0.70	7.25
SK2	-22.39	84.02	6.22	6.53	0.99	0.30	0.71	6.38
SK3	-29.99	83.25	5.86	7.28	0.99	0.27	0.73	8.08
SK1	-85.54	80.13	4.75	11.39	1.00	0.17	0.82	18.53

Notes : * Calculated from molecular weights. Sample numbers are arranged in order of increased degree of weathering.

Table 23 - Chemical Weathering Indices, Weathered Fine Ash Tuff, Tseung Kwan O

Sample No.	Weathering Potential Index*	Weathering Product Index*	Silica to Alumina Ratio*	Alumina to Potassium Sodium Ratio	Alumina to Calcium Sodium Ratio	Lixiviation Index	Mobiles Index*	Loss on Ignition
TK01	8.00	84.02	6.32	2.26	0.71	0.10	0.00	1.39
TK02	-2.41	83.68	6.20	2.49	0.79	0.13	0.23	3.39
TK03	-14.93	83.10	5.84	2.39	0.85	0.19	0.32	6.10
TK05	-28.10	80.07	5.11	6.30	0.99	0.29	0.79	7.70
TK04	-66.54	77.52	4.18	8.01	0.99	0.25	0.82	15.36
TK06(1)	-19.70	85.06	6.43	4.92	0.99	0.42	0.76	5.77
TK07(1)	-29.59	81.47	5.09	7.63	0.98	0.28	0.81	7.80
TK08(1)	-37.17	75.91	4.05	9.18	0.99	0.23	1.00	9.08

Notes : * Calculated from molecular weights. Sample numbers are arranged in order of increased degree of weathering.

Table 24 - Chemical Weathering Indices, Weathered Fine Ash Tuff, Ap Tsai, Tseung Kwan O

Sample No.	Weathering Potential Index*	Weathering Product Index*	Silica to Alumina Ratio*	Alumina to Potassium Sodium Ratio	Alumina to Calcium Sodium Ratio	Lixiviation Index	Mobiles Index*	Loss on Ignition
ATW1	6.29	89.63	9.56	1.70	0.78	0.14	0.00	0.50
ATW3F	6.91	86.27	7.38	1.74	0.76	0.16	0.00	0.99
ATW2	7.79	85.90	7.14	1.76	0.75	0.17	-0.03	0.83
ATW3	3.69	86.02	7.28	1.71	0.79	0.20	0.07	1.64
ATW3S	0.40	85.77	7.18	1.69	0.82	0.33	0.13	2.29
ATW4	-46.54	84.98	6.68	4.57	0.99	0.32	0.73	11.64
ATW5	-23.79	87.89	8.46	2.78	0.98	0.55	0.61	7.10
ATW6	-41.27	83.30	5.82	10.47	0.99	0.15	0.86	10.13

Notes : * Calculated from molecular weights. Sample numbers are arranged in order of increased degree of weathering.

Table 25 - Micropetrographic Indices for Weathered Coarse Ash Tuff, Aberdeen

Description	Sample No.	Altered Minerals %	Sound Minerals %	Microcracks and Voids %	Micropetrographic Index Ip
Slightly Decomposed	IR1	11.8	88.1	0.1	7.87
Moderately Decomposed	IR2	24.9	73.7	1.3	2.81
Highly Decomposed	IR4	43.0	34.9	22.0	0.54
Completely Decomposed	IR5	58.1	29.6	12.2*	0.42
Transition Soil	IR6	64.5	19.8	15.6*	0.25

Notes : * Percentage of pores could be higher. Differentiation between minute altered areas and pores is not possible under the normal resolution power of microscope.

LIST OF FIGURES

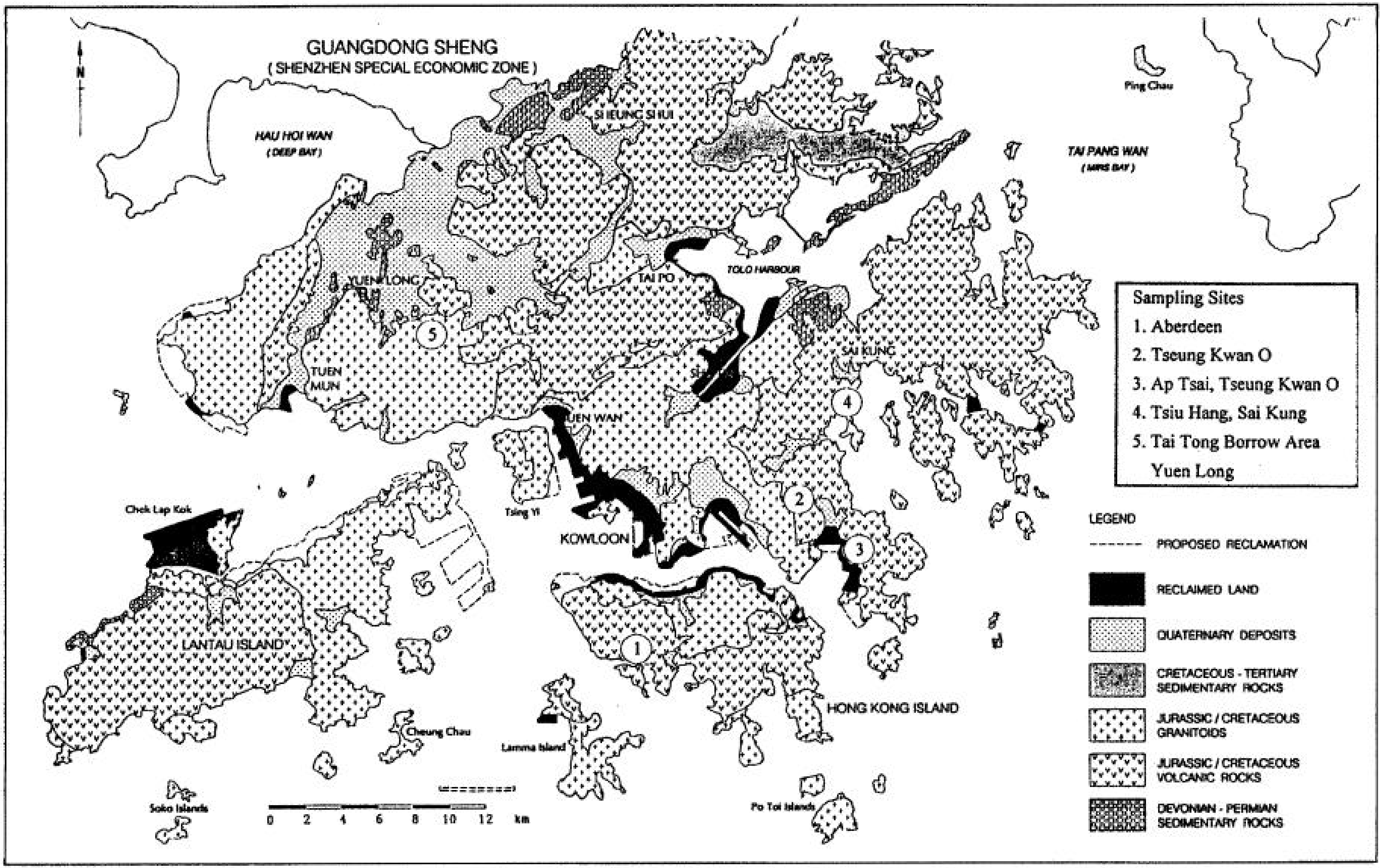


Figure 1 - Geological Map of Hong Kong and Sampling Locations

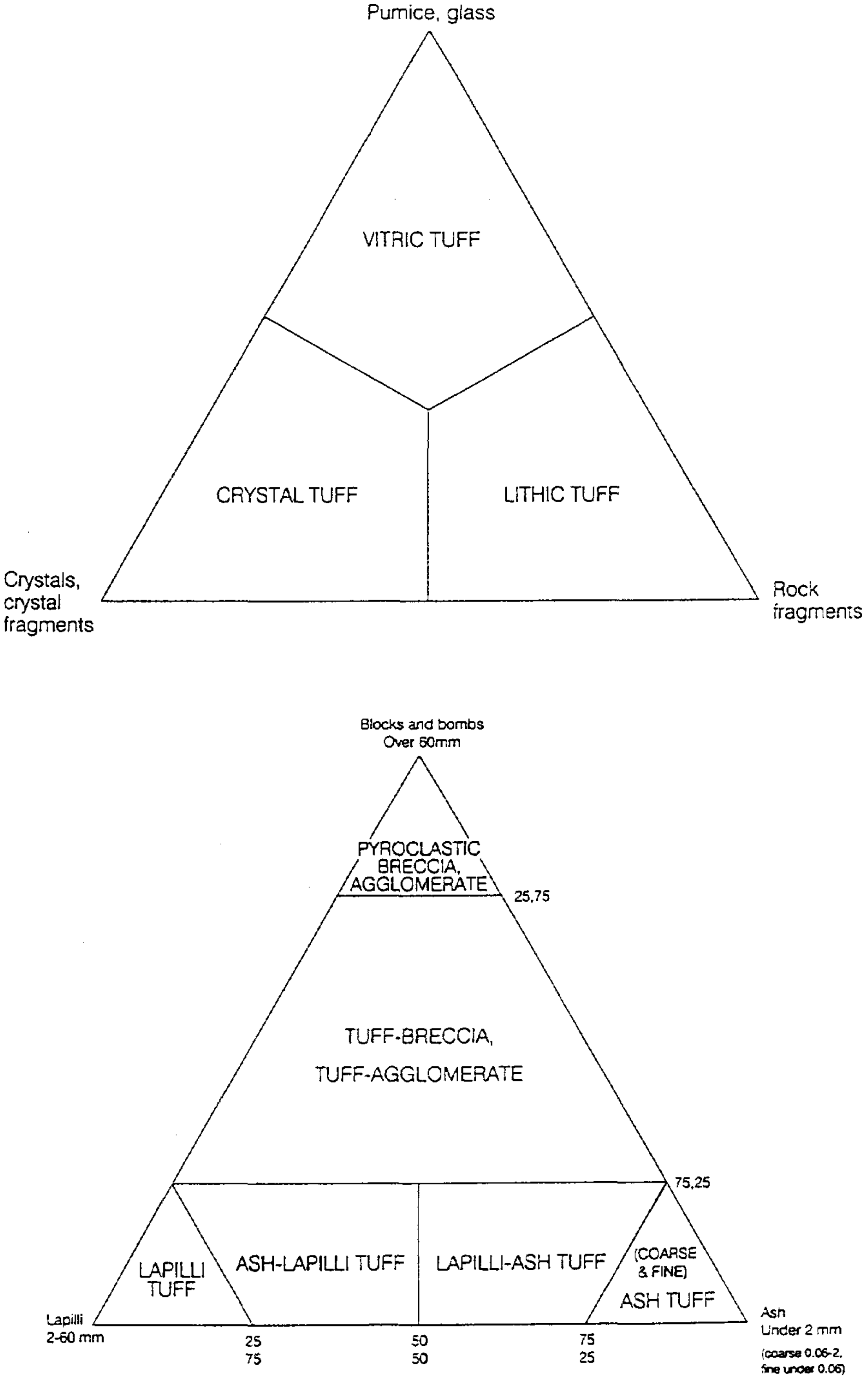


Figure 2 - Classification of Pyroclastic Volcanic Rocks

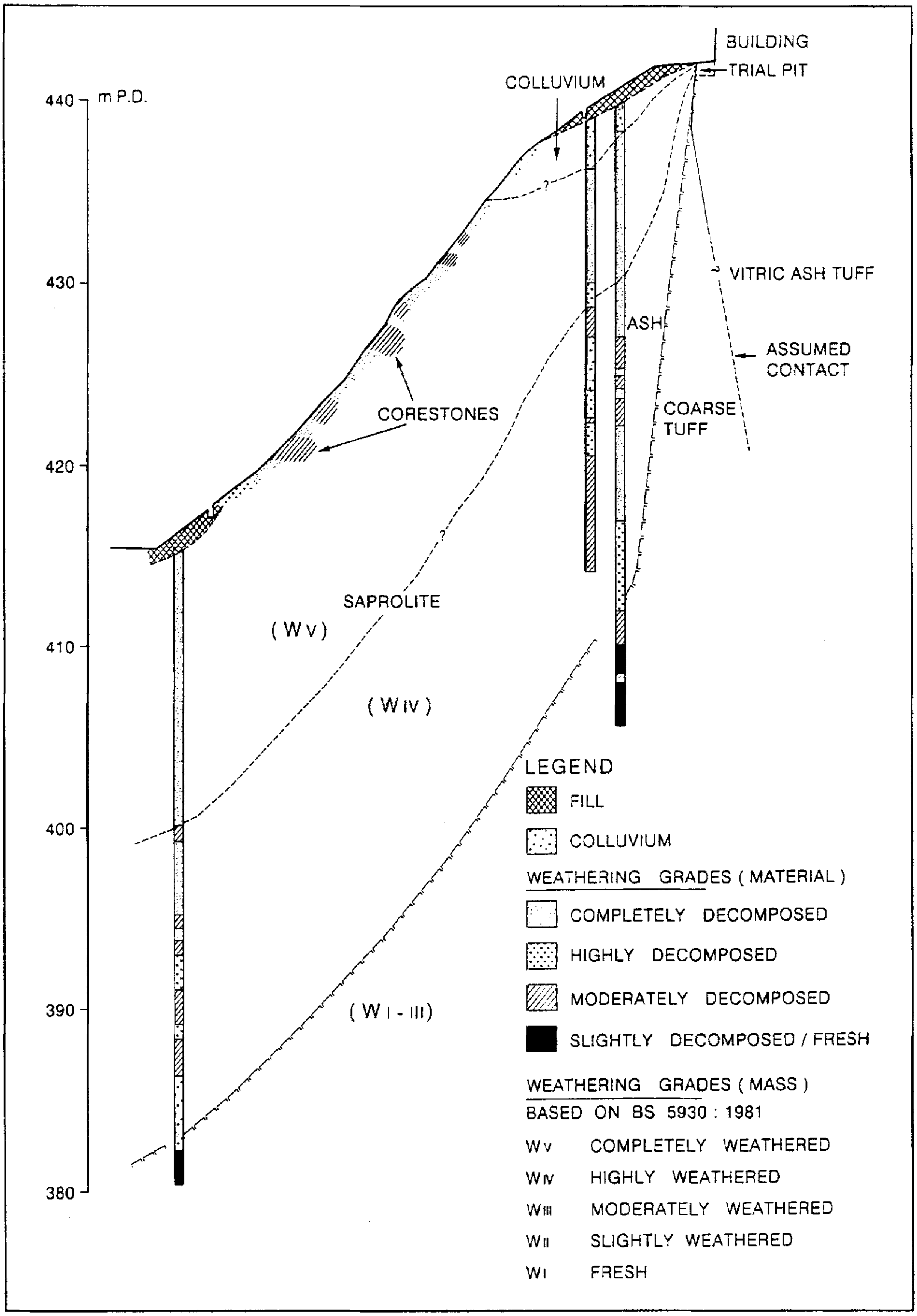


Figure 3 - Weathering Profile in Coarse Ash Tuff, The Peak

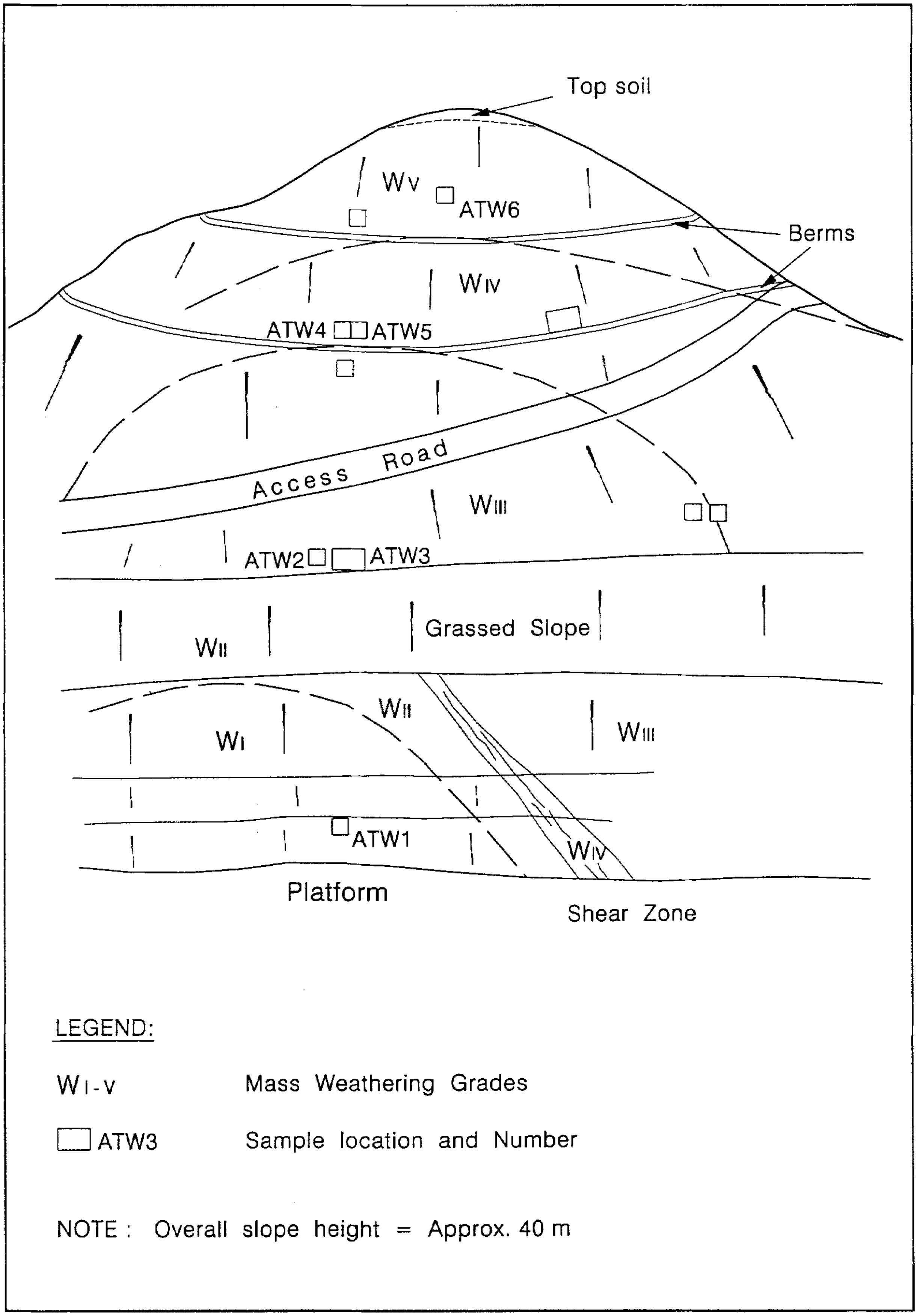
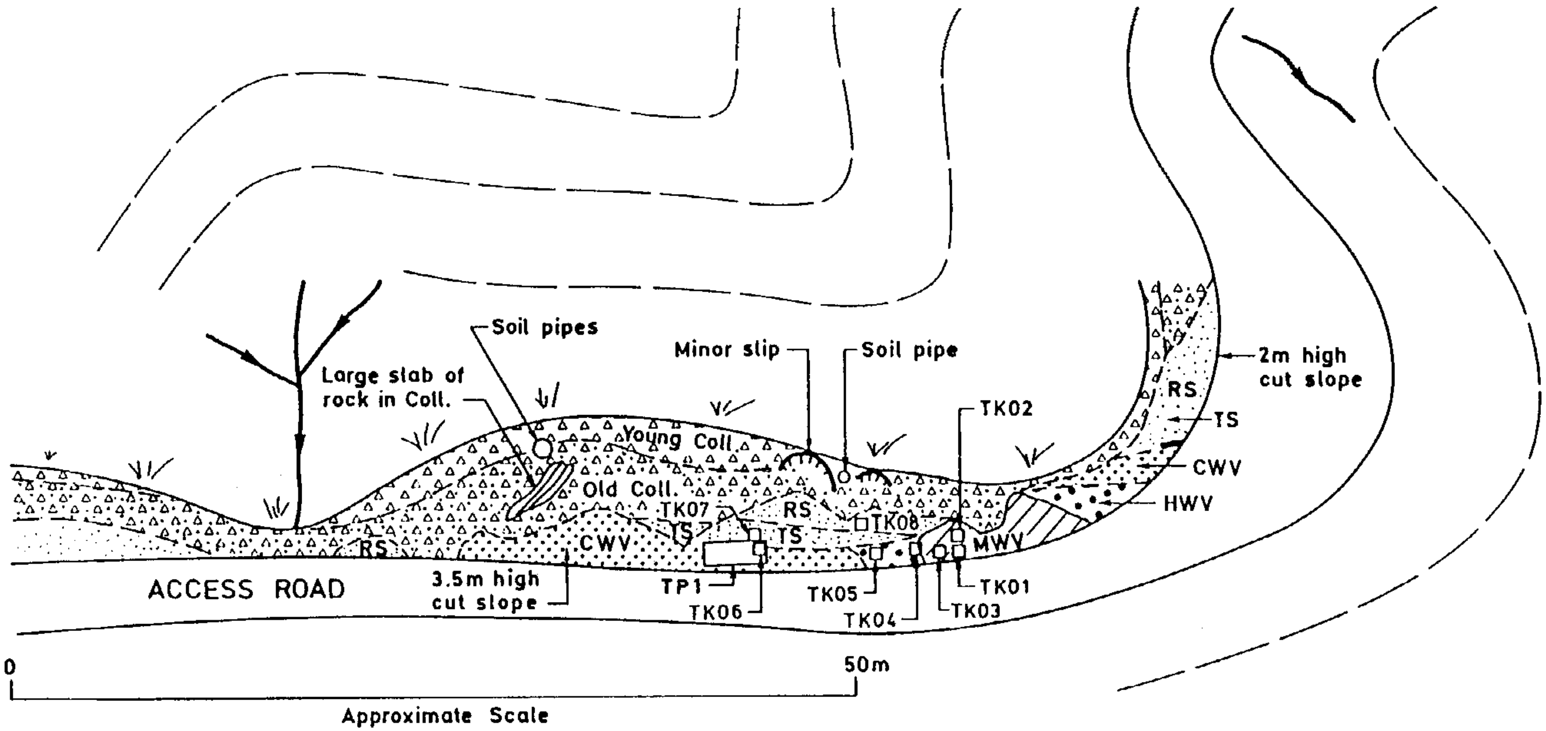


Figure 4 - Sketch of Weathering Profile in Fine Ash Tuff, Tseung Kwan O



Legend :

CWV	Completely Weathered Volcanic	RS	Residual Soil
HWV	Highly Weathered Volcanic	TS	Transition Soil
MWV	Moderately Weathered Volcanic (Fine Ash Tuff)	Coll.	Colluvium
□TK01	Sample Location		

Figure 5 - Sketch of Weathering Profile in Fine Ash Tuff, Ap Tsai, Tsueng Kwan O

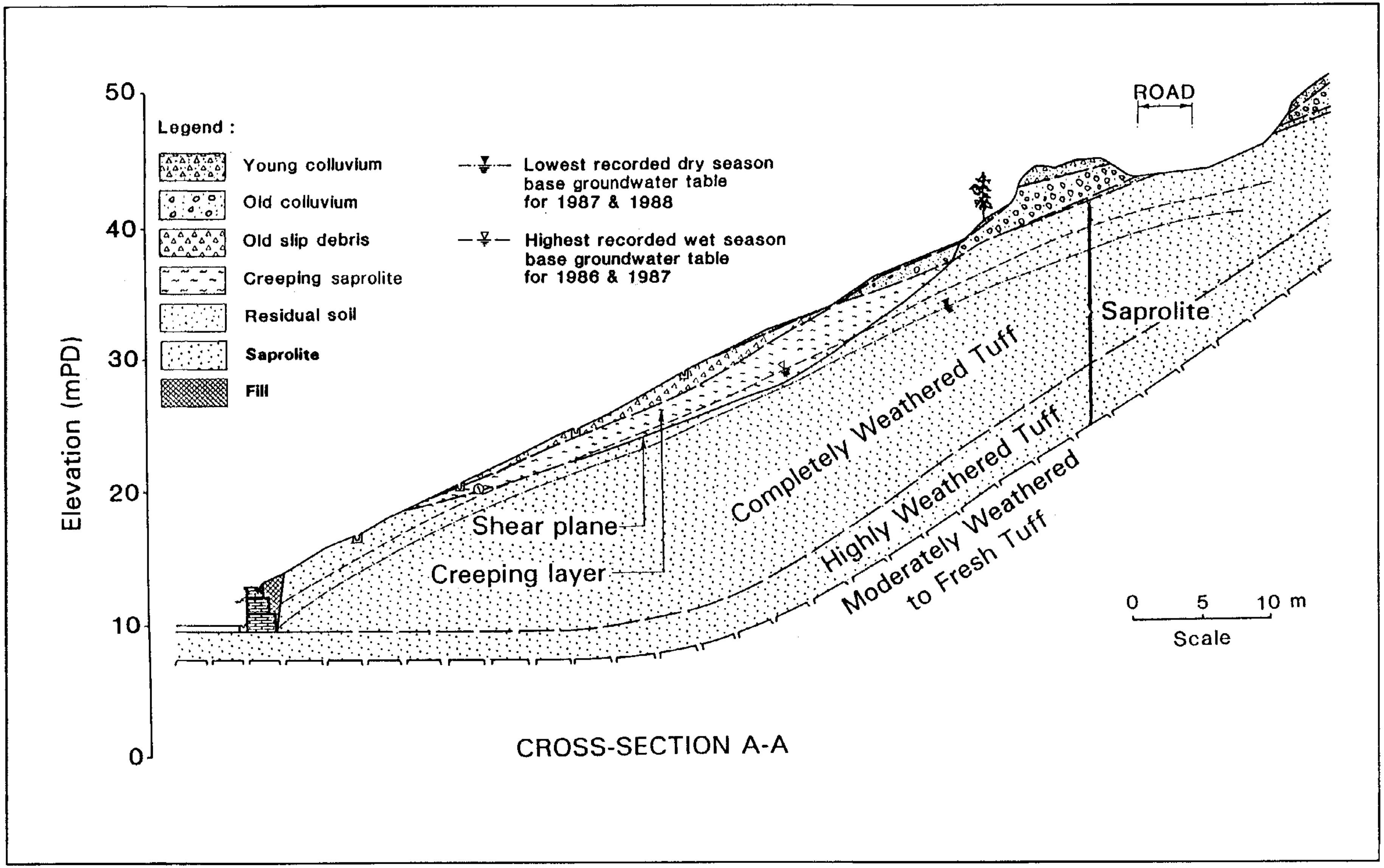


Figure 6 - Weathering Profile in Coarse Ash Tuff, Aberdeen (Prior to the Landslide)

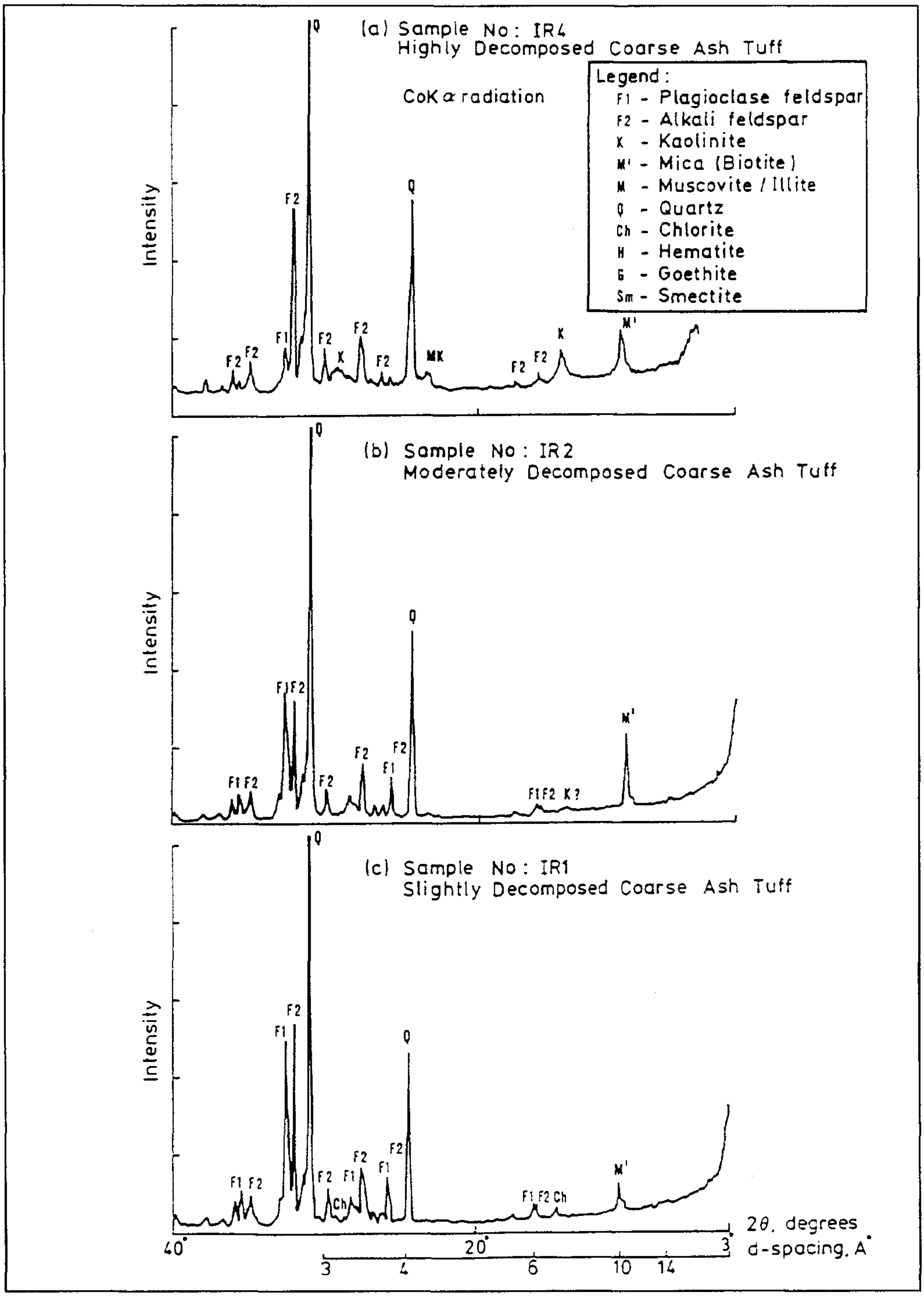


Figure 7 - Whole Rock XRD Scans of Slightly, Moderately and Highly Decomposed Coarse Ash Tuff

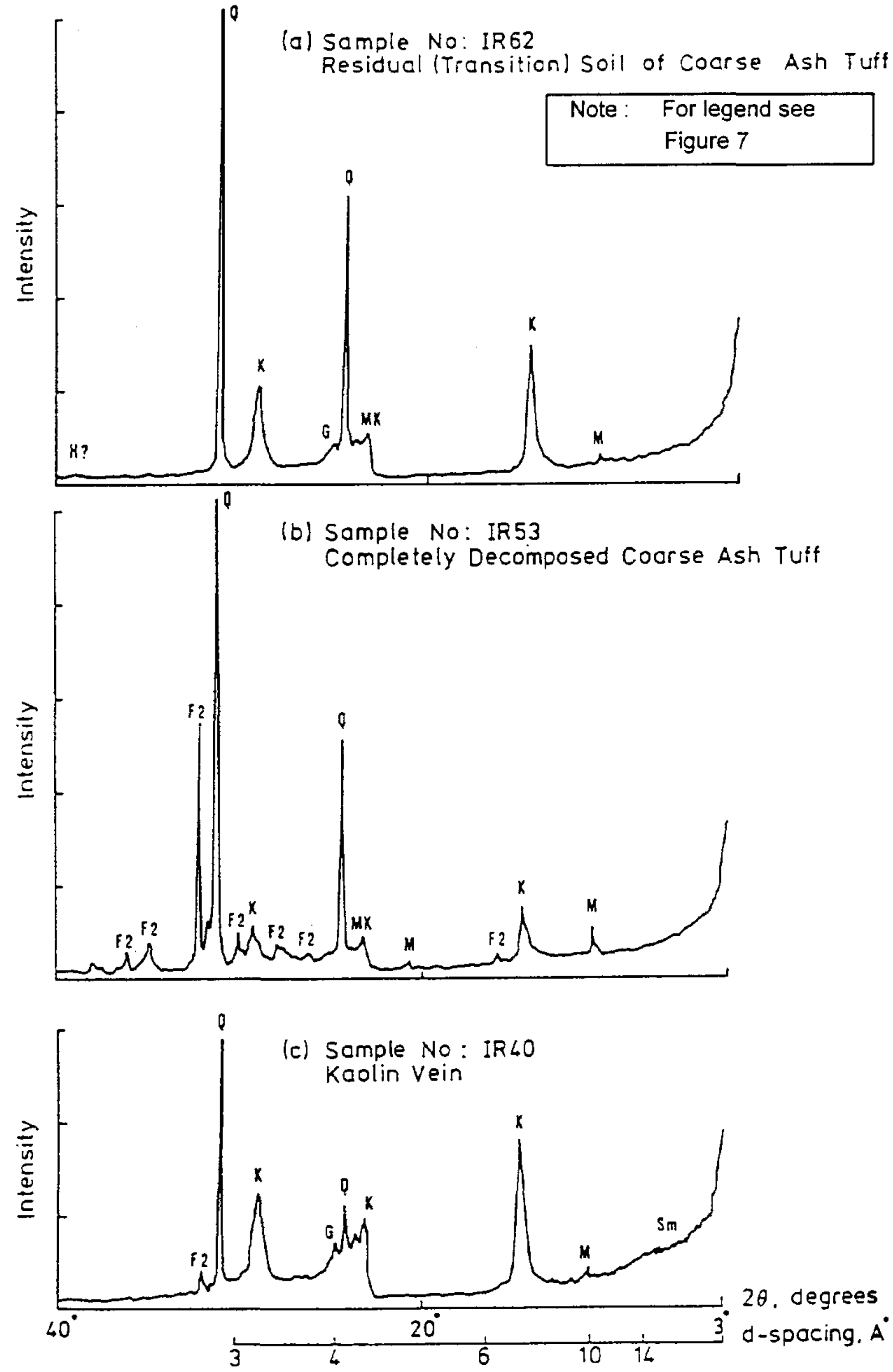


Figure 8 - Whole Rock XRD Scans of Completely Decomposed and Residual Soil of Coarse Ash Tuff

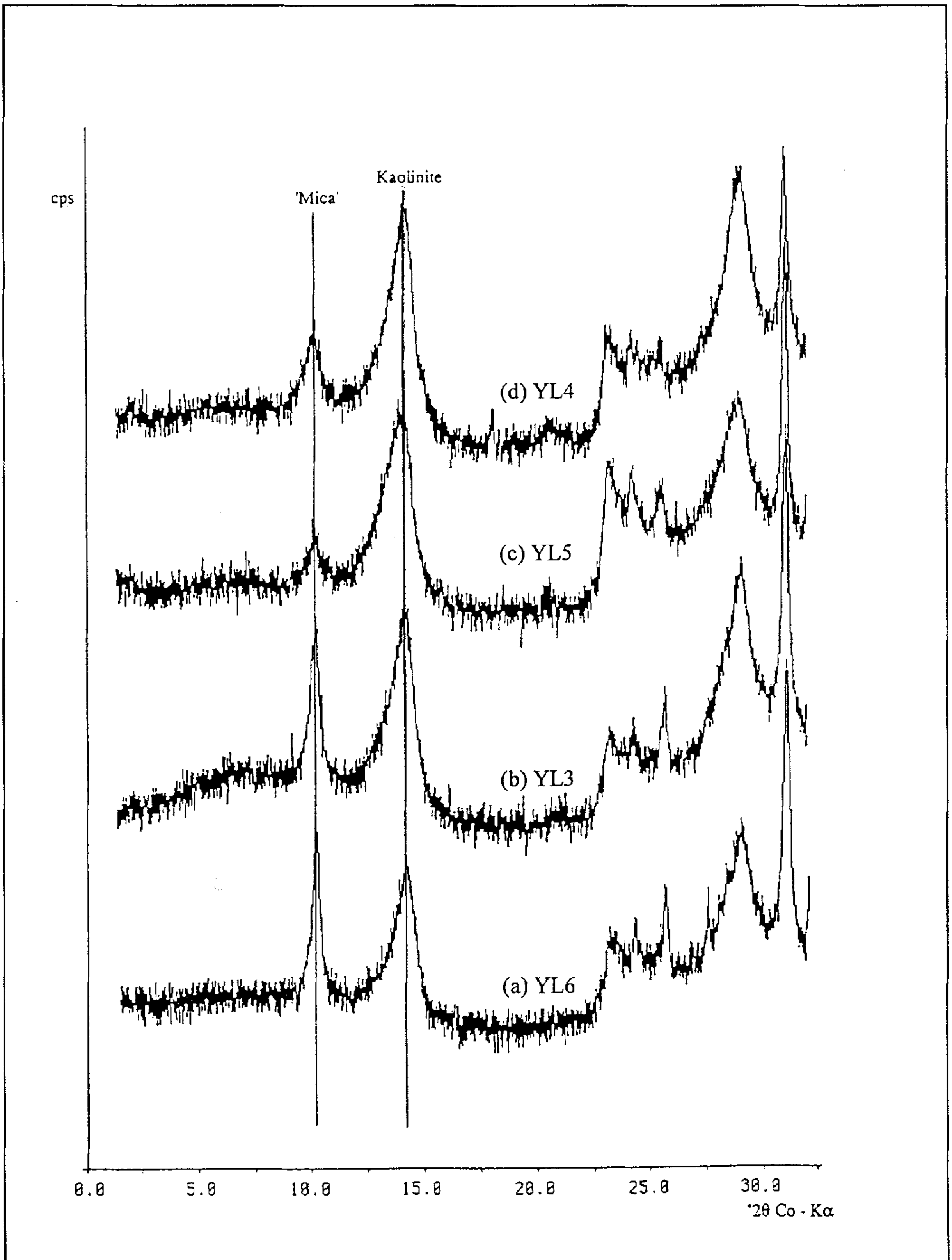


Figure 9 - Clay Portion XRD Scans of Weathered Coarse Ash Tuff, Yuen Long

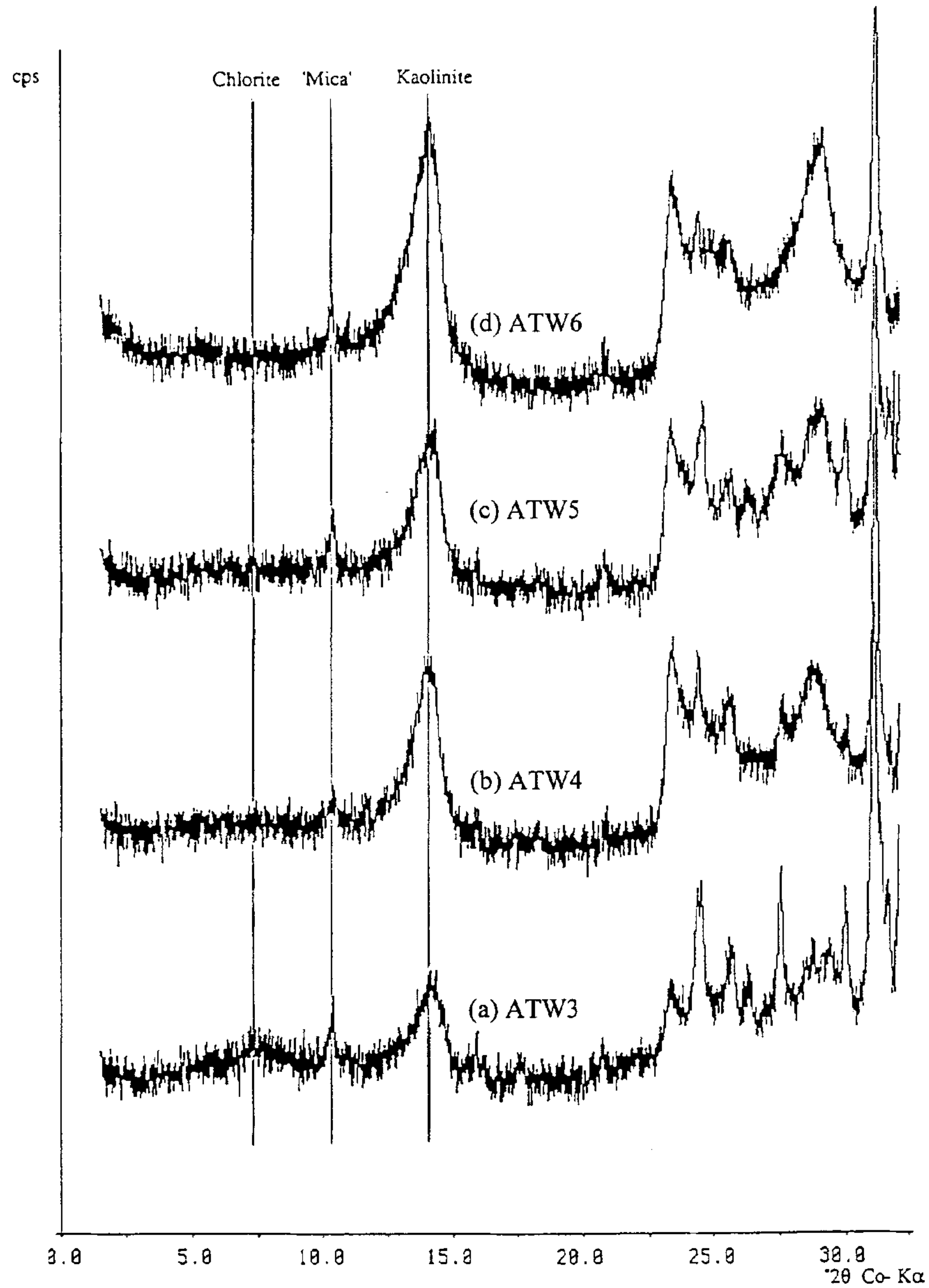
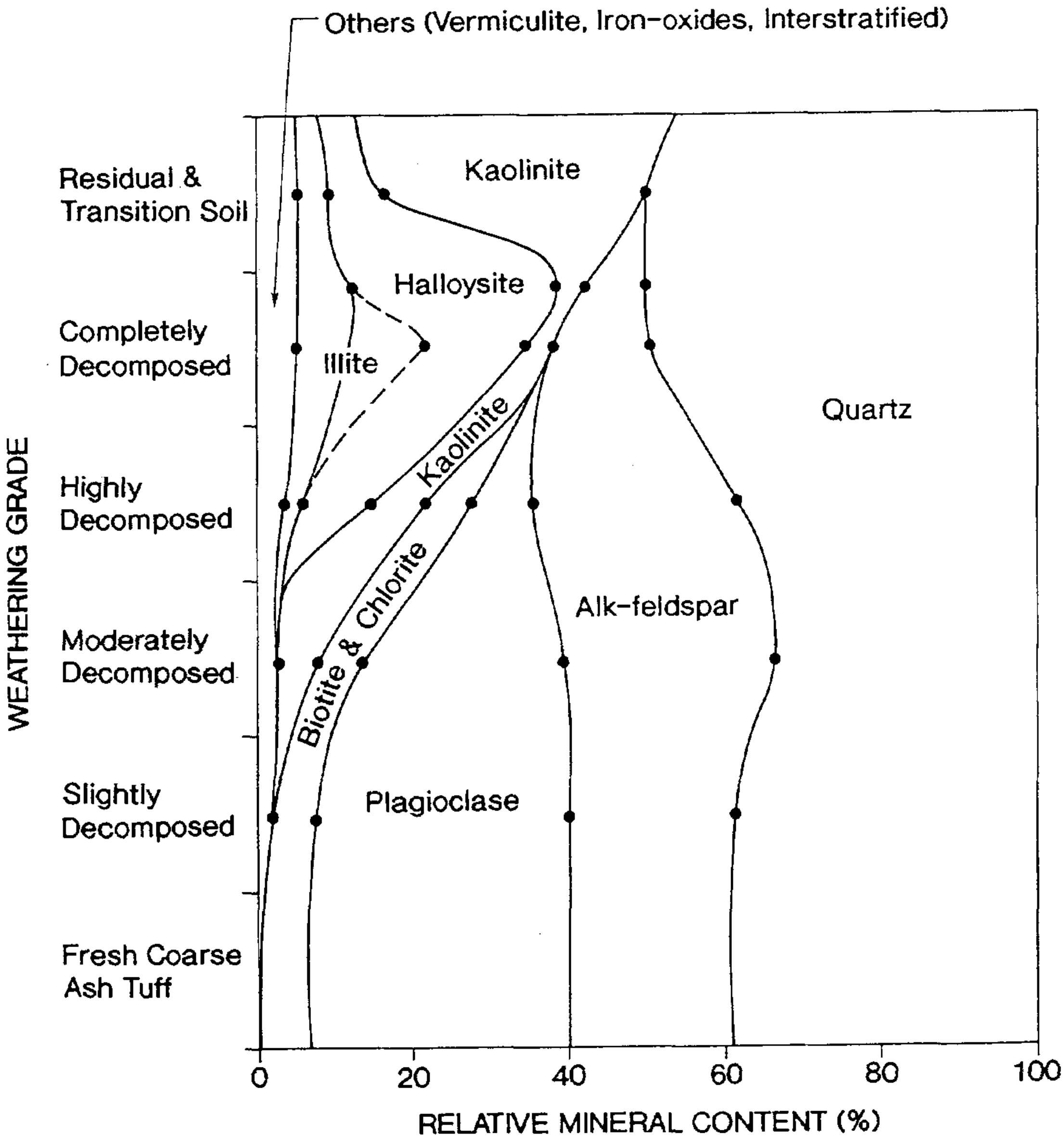


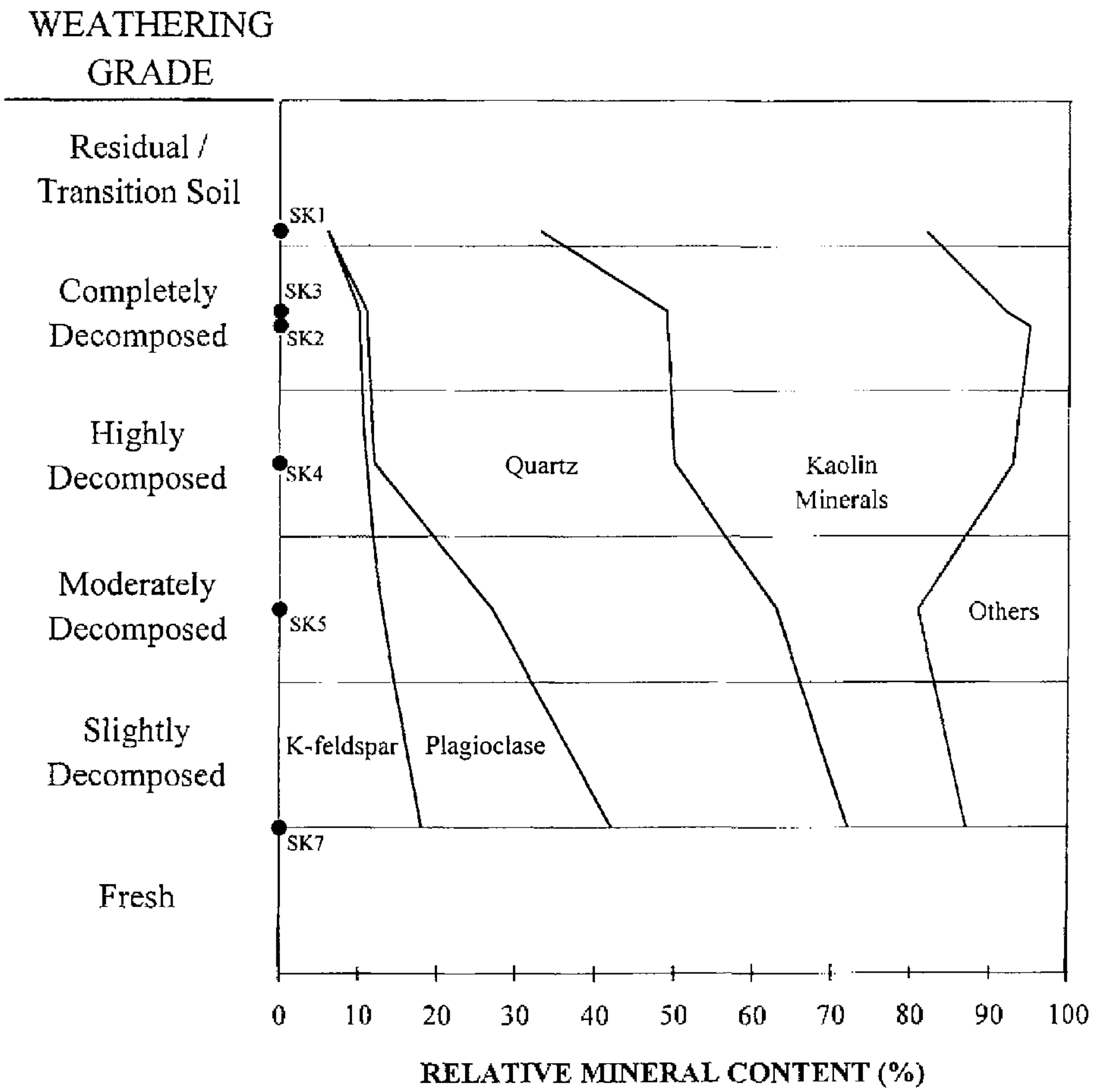
Figure 10 - Clay Portion XRD Scans of Weathered Fine Ash Tuff, Ap Tsai, Tseung Kwan O



Notes : (1) Broken line–increase in illite is probably due to possible hydrothermal effects.

(2) Purpose of figure is to show general trends, discrepancies are expected due to sample variation etc.

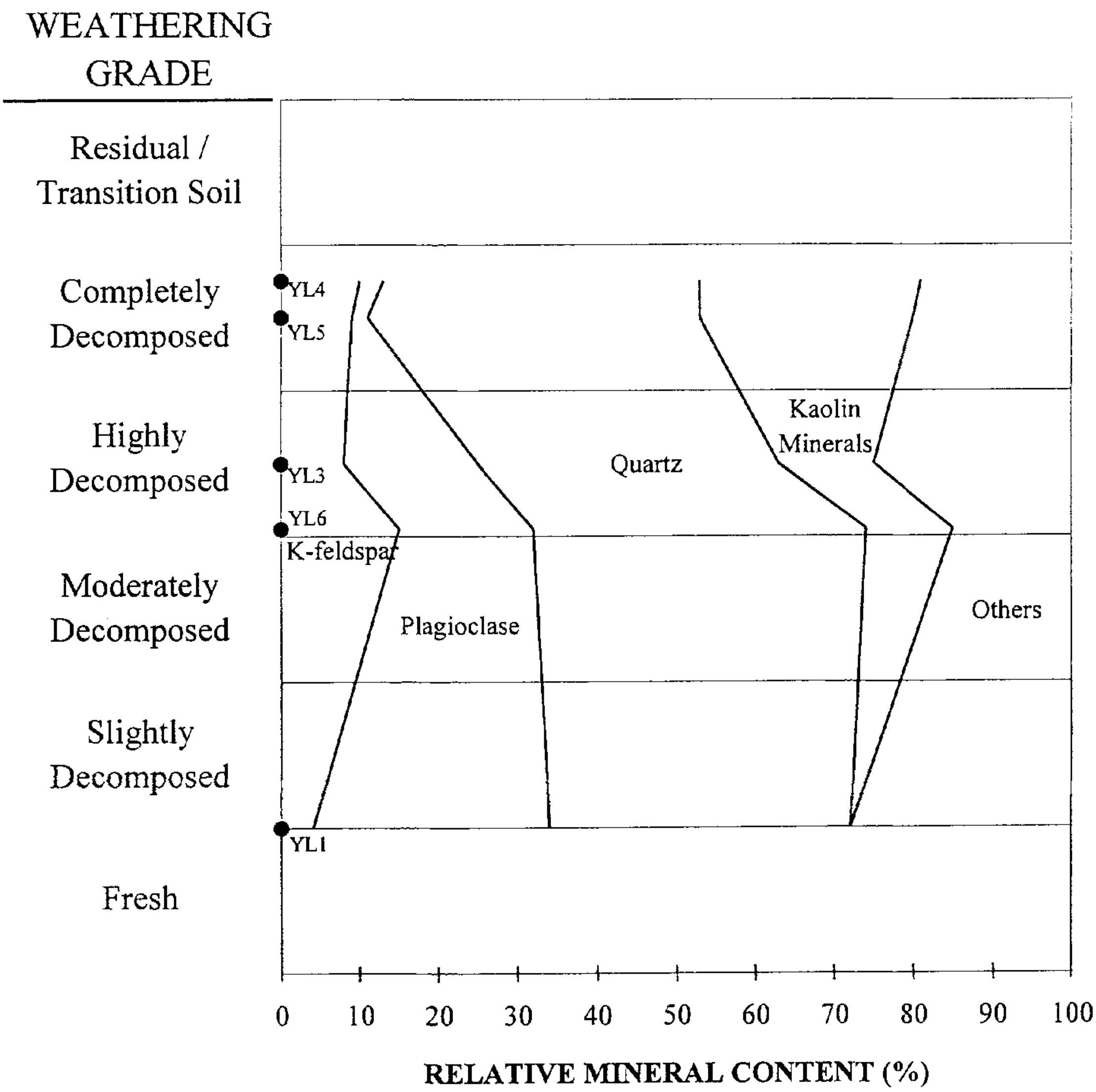
Figure 11 - Variation in Mineralogical Composition with Weathering, Coarse Ash Tuff, Aberdeen



Notes :

1. Other minerals include fine-grained micas (up to 10%), iron oxides and hydroxides (usually 3 to 5%) and trace amounts of chlorite, vermiculite.
2. SK1 Relative approximate location of sample analysed within the weathering grade.
3. Kaolin mineral contents of fresher samples are attributed to contact metamorphism, hydrothermal alteration and other alteration processes prior to weathering.

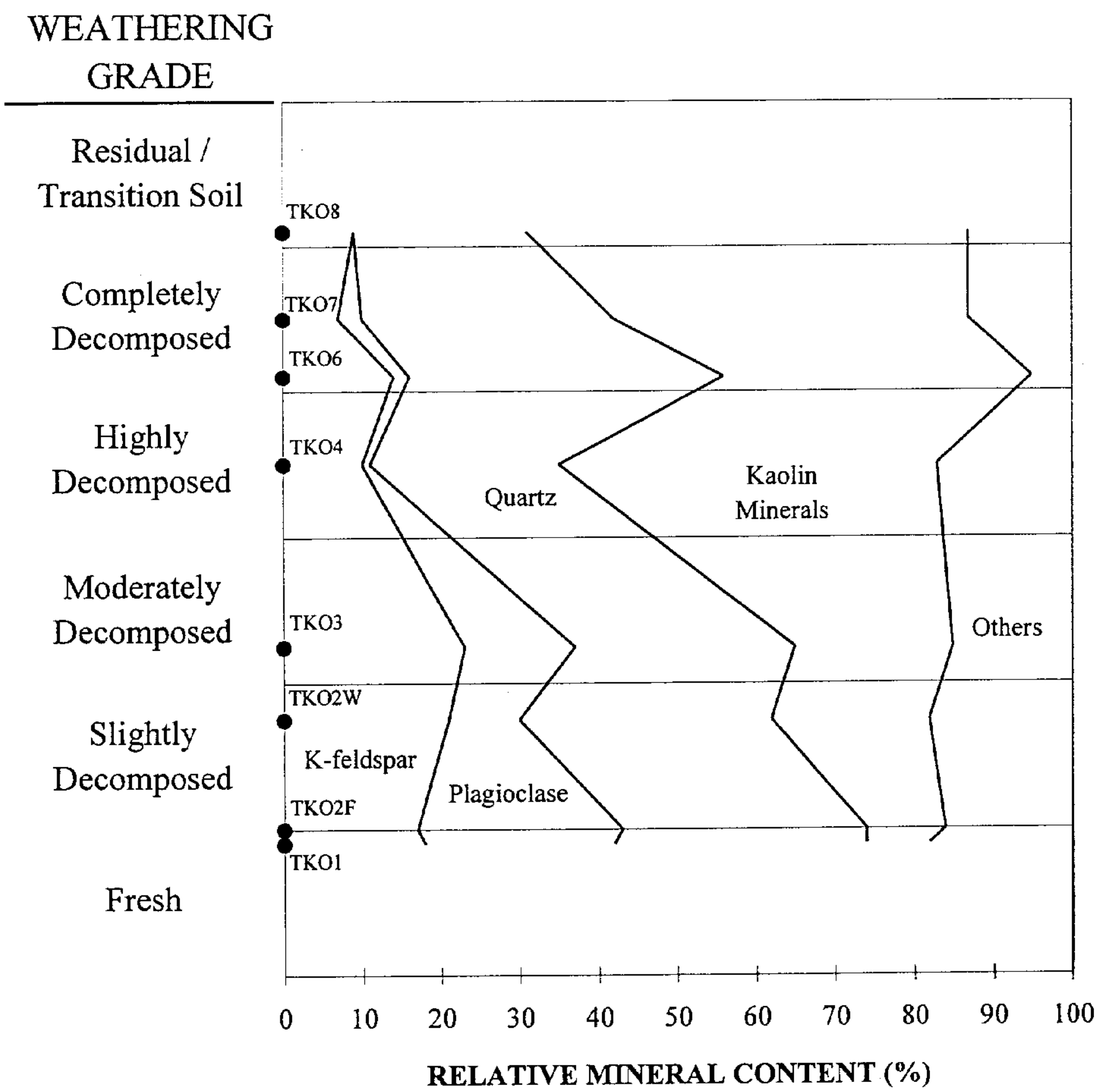
Figure 12 - Variation in Mineralogical Composition with Weathering, Coarse Ash Tuff, Sai Kung



Notes :

1. Other minerals include fine-grained micas (up to 10%), iron oxides and hydroxides (usually 3 to 5%) and trace amounts of chlorite, vermiculite.
2. YL1 Relative approximate location of sample analysed within the weathering grade.
3. Kaolin mineral contents of fresher samples are attributed to contact metamorphism, hydrothermal alteration and other alteration processes prior to weathering.

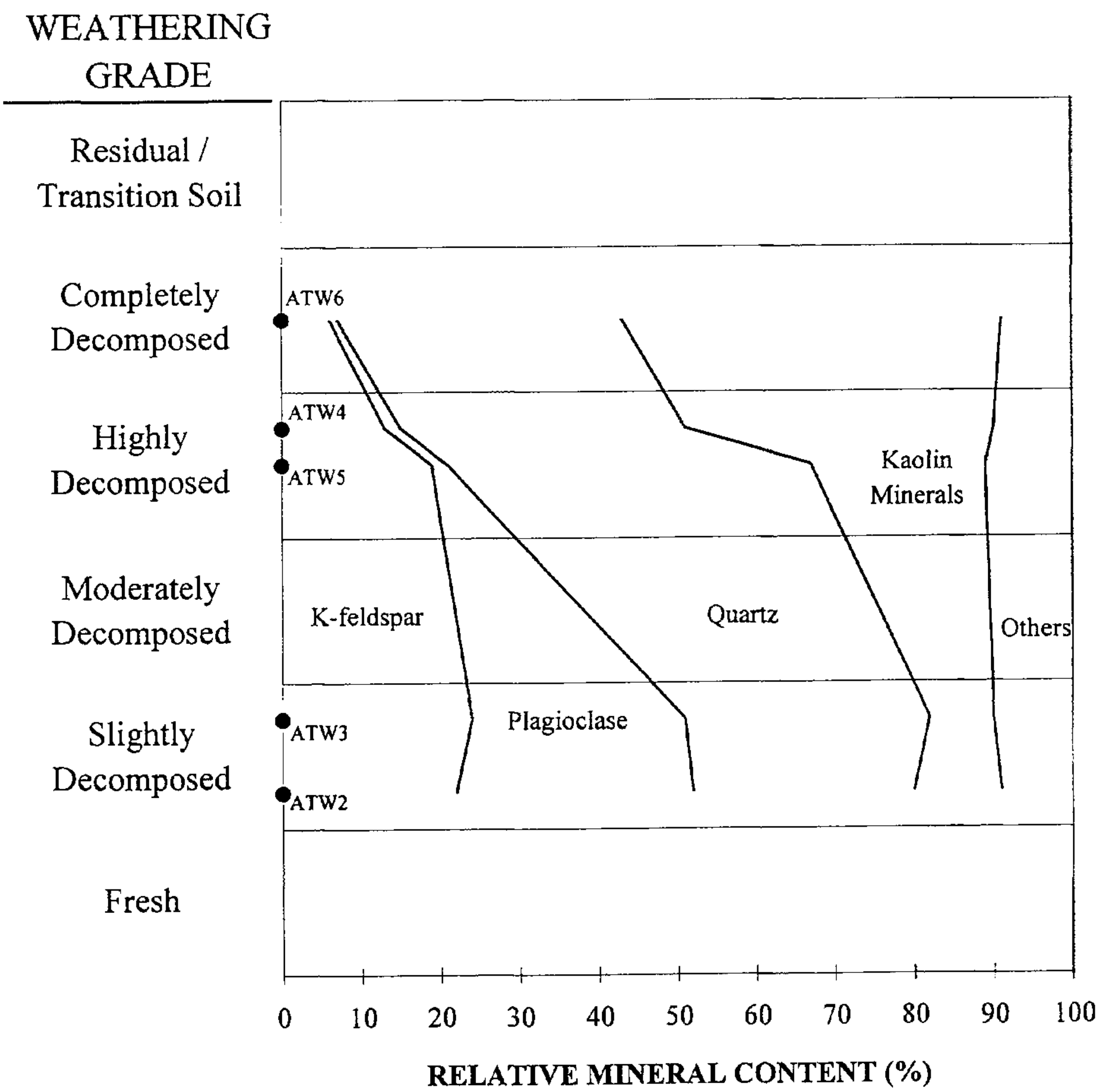
Figure 13 - Variation in Mineralogical Composition with Weathering, Coarse Ash Tuff, Yuen Long



Notes :

1. Other minerals include fine-grained micas (up to 10%), iron oxides and hydroxides (usually 3 to 5%) and trace amounts of chlorite, vermiculite.
2. TKO1 Relative approximate location of sample analysed within the weathering grade.
3. Kaolin mineral contents of fresher samples are attributed to contact metamorphism, hydrothermal alteration and other alteration processes prior to weathering.

Figure 14 - Variation in Mineralogical Composition with Weathering, Fine Ash Tuff, Tseung Kwan O



Notes :

1. Other minerals include fine-grained micas (up to 10%), iron oxides and hydroxides (usually 3 to 5%) and trace amounts of chlorite, vermiculite.
2. ATW2 Relative approximate location of sample analysed within the weathering grade.
3. Kaolin mineral contents of fresher samples are attributed to contact metamorphism, hydrothermal alteration and other alteration processes prior to weathering.

Figure 15 - Variation in Mineralogical Composition with Weathering, Fine Ash Tuff, Ap Tsai, Tseung Kwan O

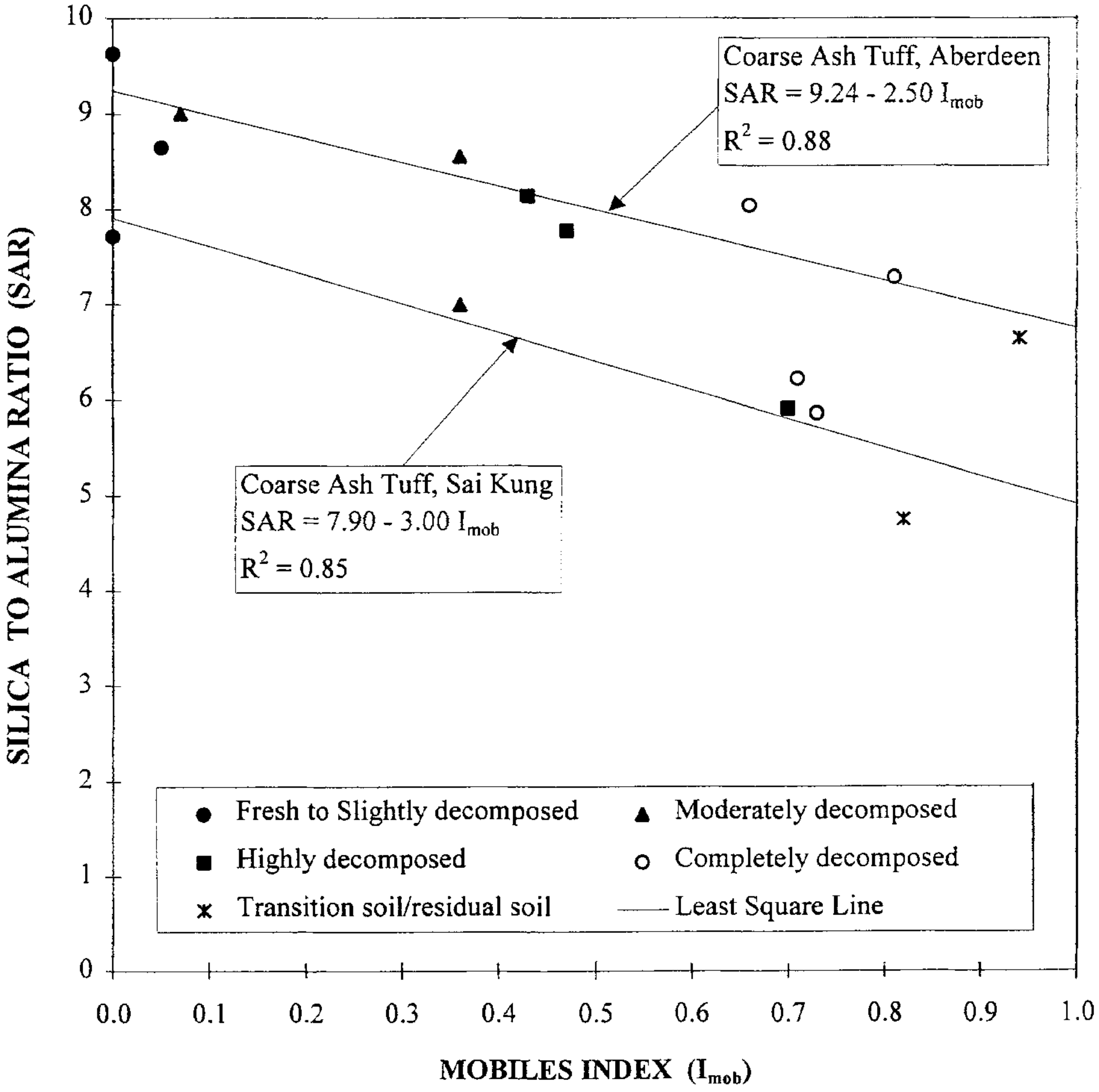


Figure 16 - Variation in Chemical Indices for Weathered Coarse Ash Tuffs from Different Localities

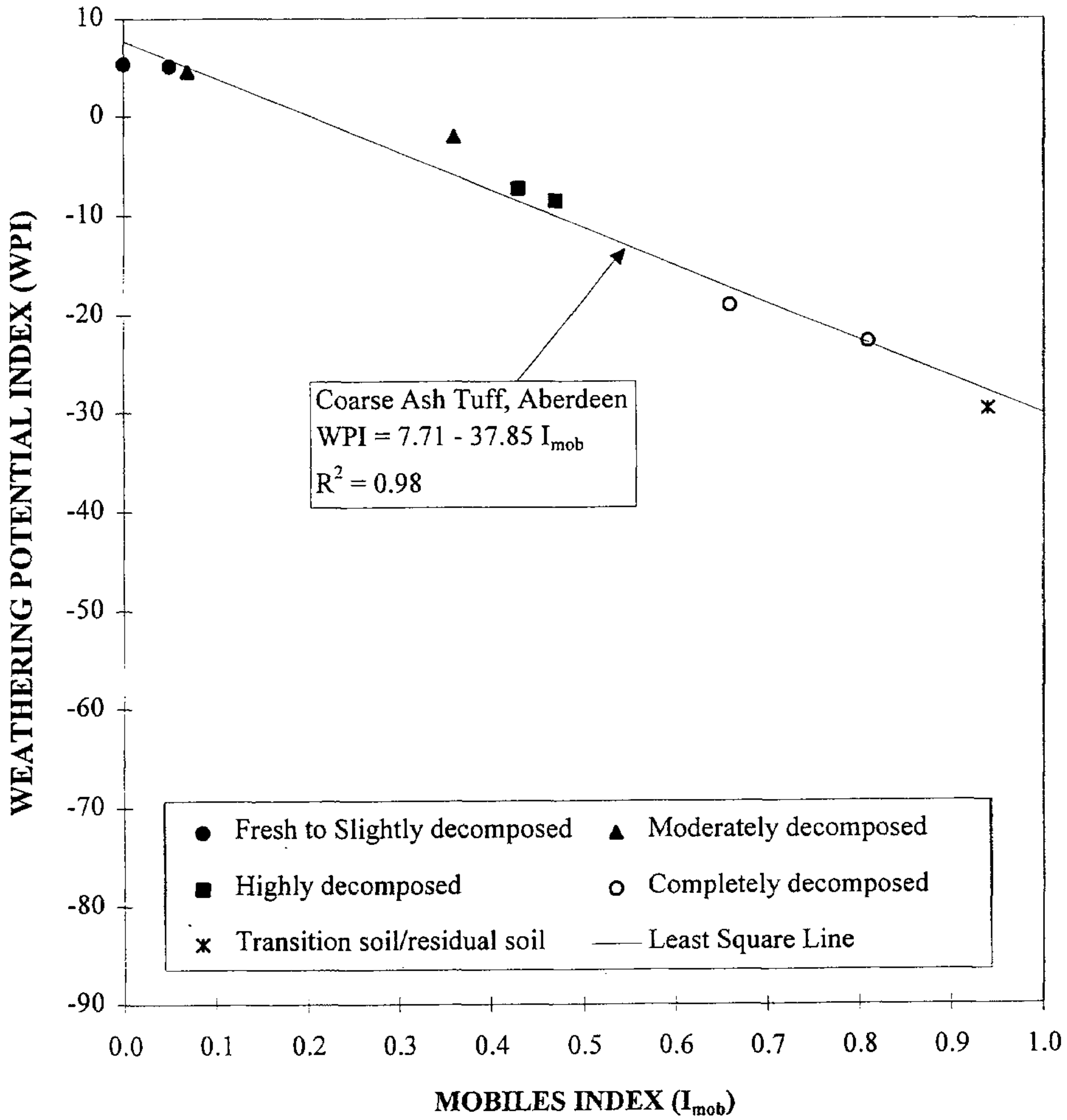


Figure 17 - Weathering Potential Index Versus Mobiles Index, Coarse Ash Tuff, Aberdeen

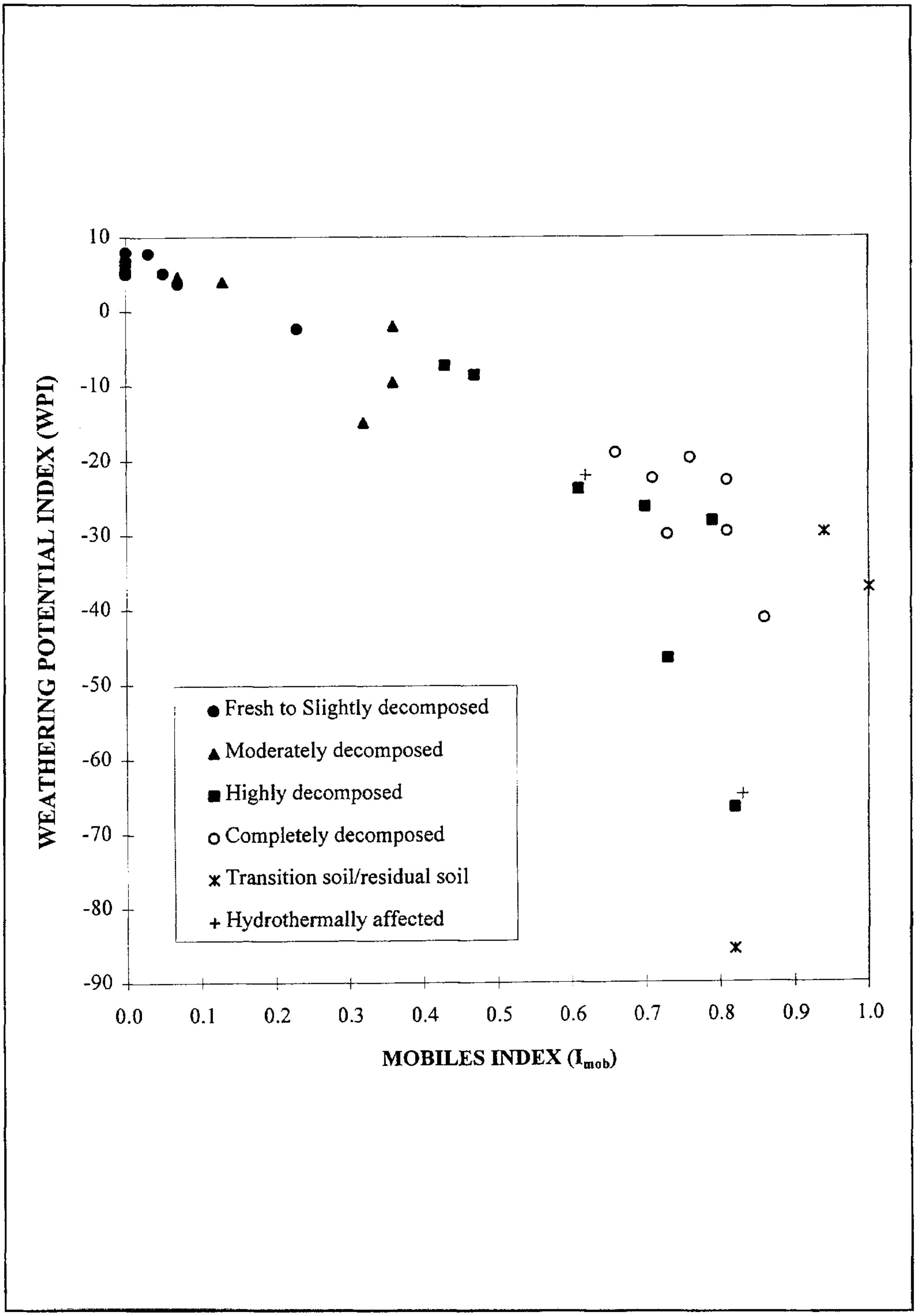


Figure 18 - Weathering Potential Index Versus Mobiles Index, All Rocks

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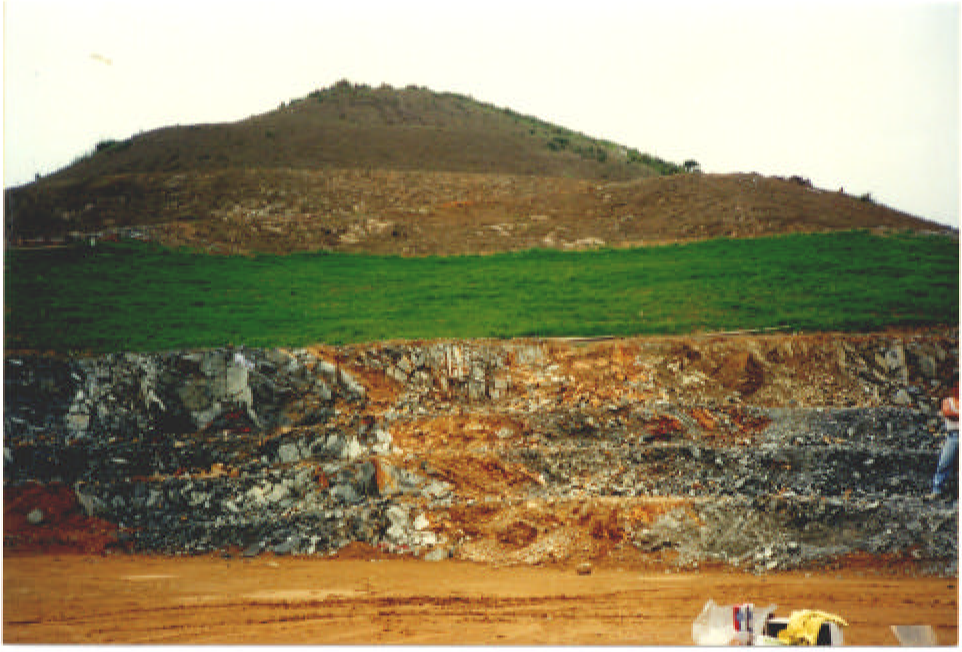
Plate 1 - Weathering Profile in Coarse Ash Tuff, Mount Davis, Hong Kong Island

(Negative No. EG8906112)

Plate 2 - Complex Weathering Profile in Fine Ash Tuff, Chai Wan, Hong Kong Island

(Negative No. HQ8704609)

Plate 3 - Soil Layer Overlying Rock Layer in Fine Ash Tuff, Chai Wan, Hong Kong Island

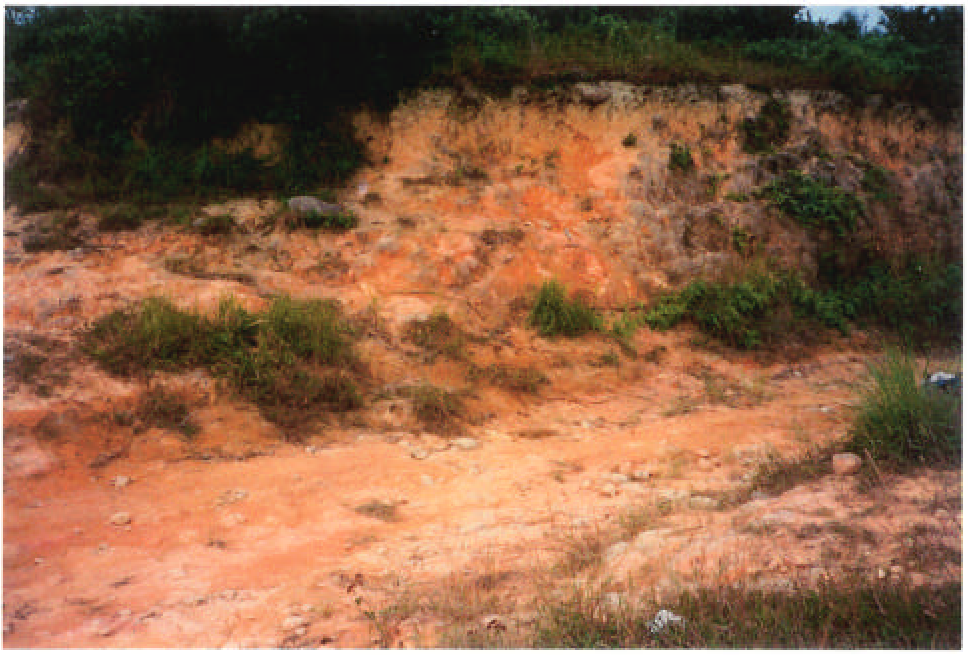


(Negative No. SP8801627)

Plate 4 - Weathering Profile in Fine Ash Tuff, Ap Tsai, Tseung Kwan O

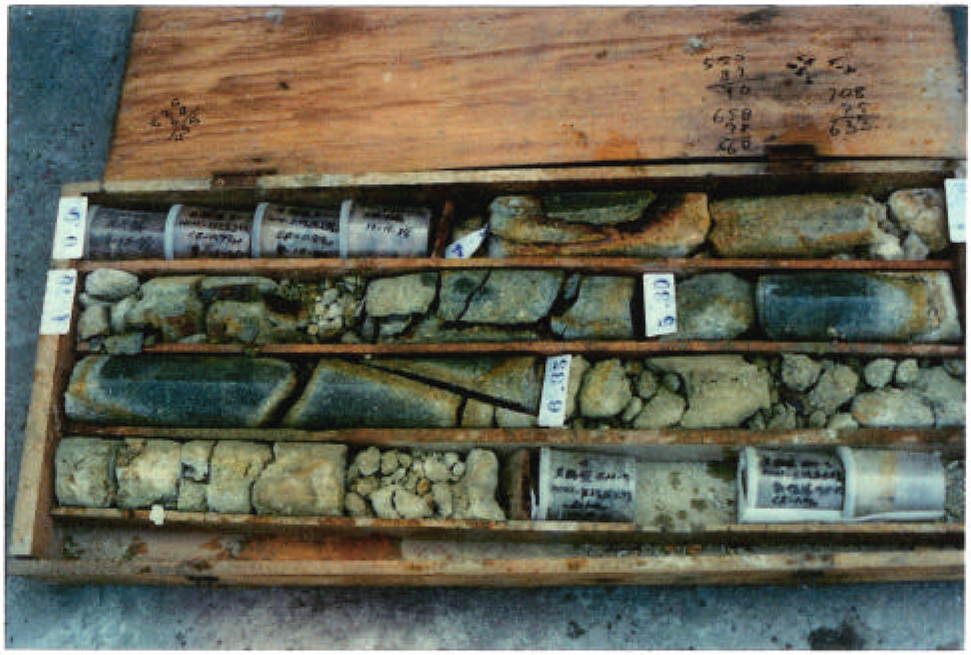
(Negative No. SP8907835)

Plate 5 - Sampling Site at Tseung Kwan O



(Negative No. SP8812301)

Plate 6 - Sampling Site at Sai Kung

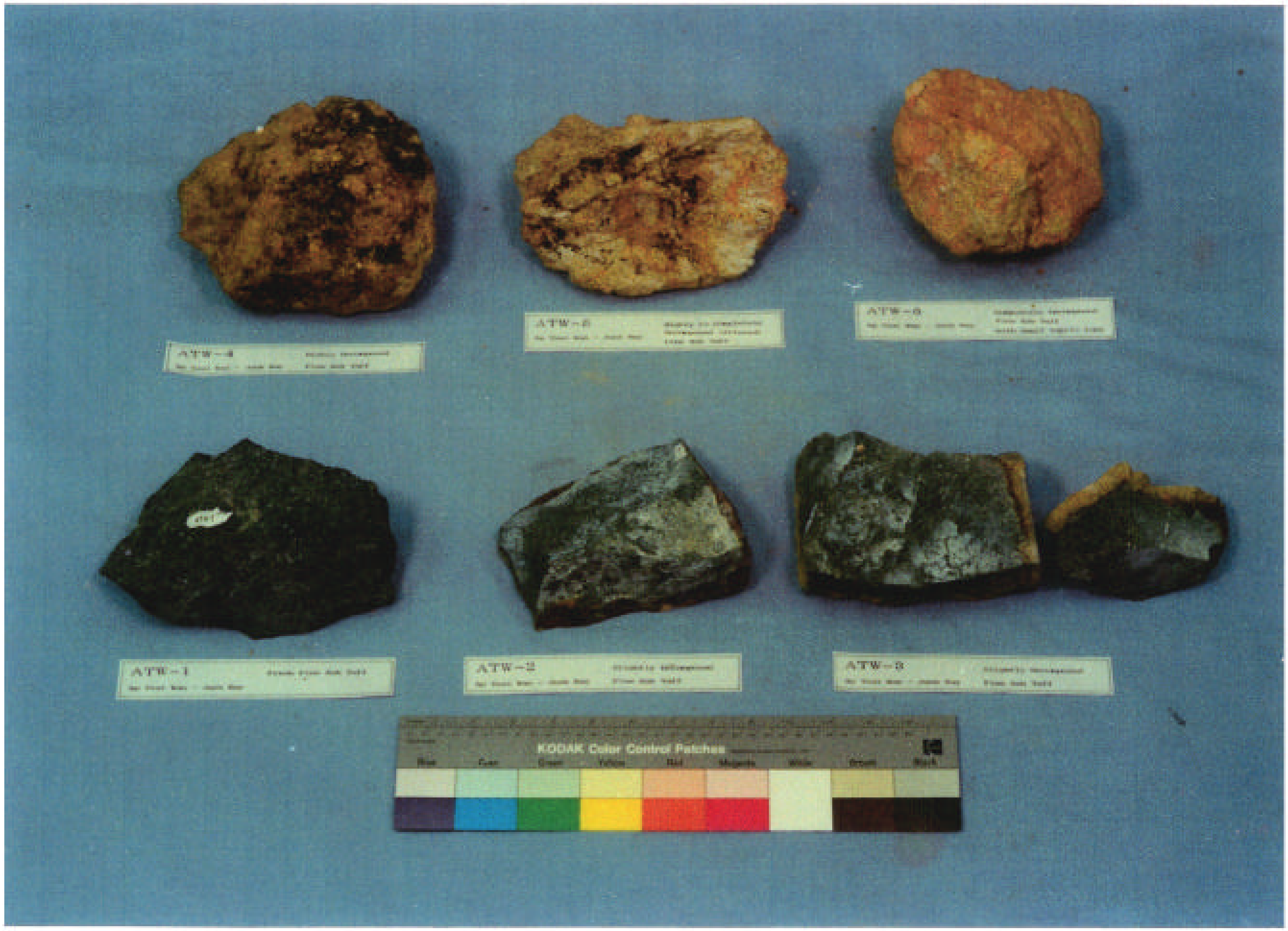


(Negative No. SP8907803 & 04)

Plate 7 - Weathered Coarse Ash Tuff Samples, Aberdeen

(Negative No. HQ9100829)

Plate 8 - Material Weathering Grades in Fine Ash Tuff, Tseung Kwan O



(Negative No. HQ9101117)

Plate 9 - Material Weathering Grades in Fine Ash Tuff (Eutaxite), Ap Tsai, Tseung Kwan O

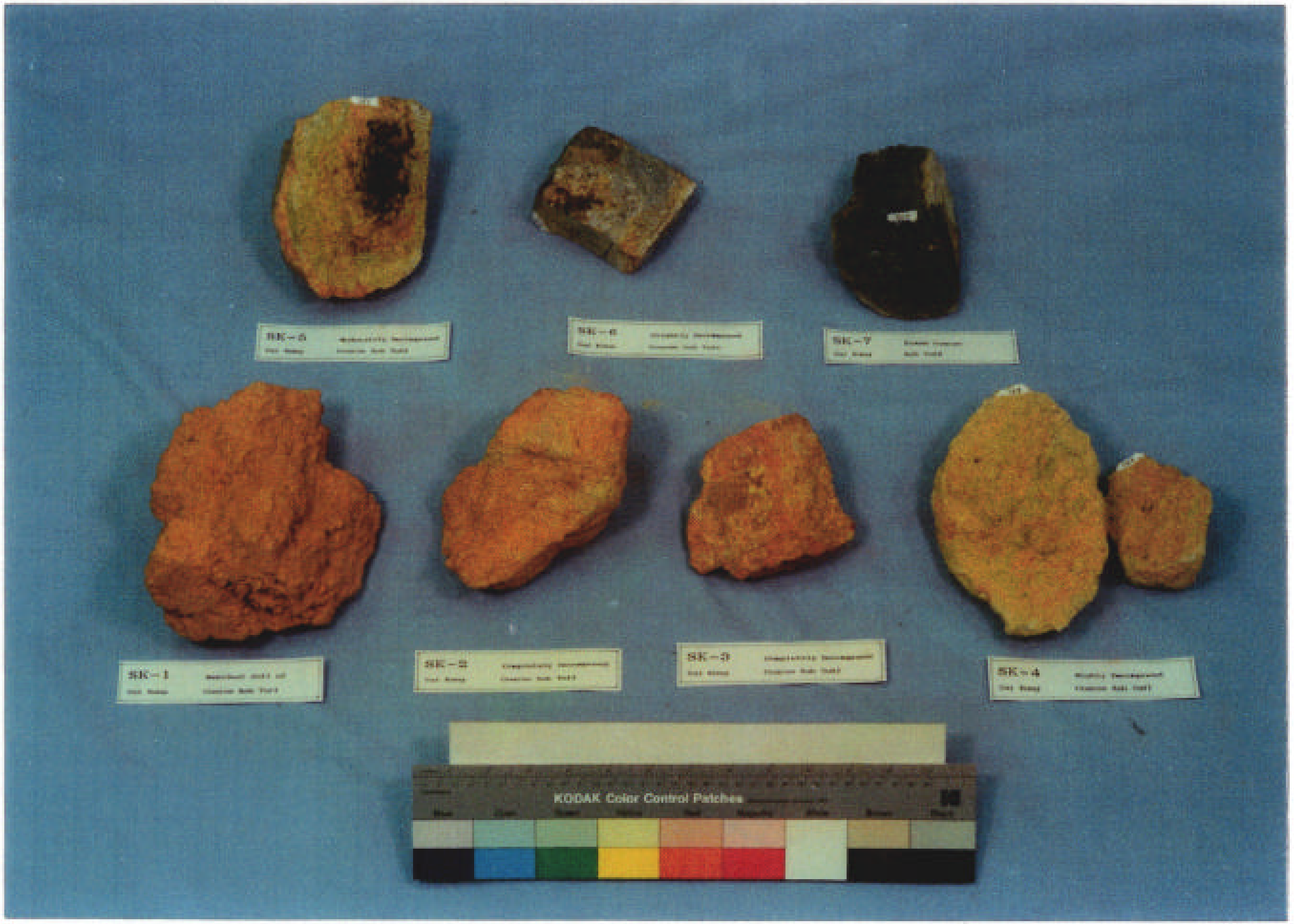


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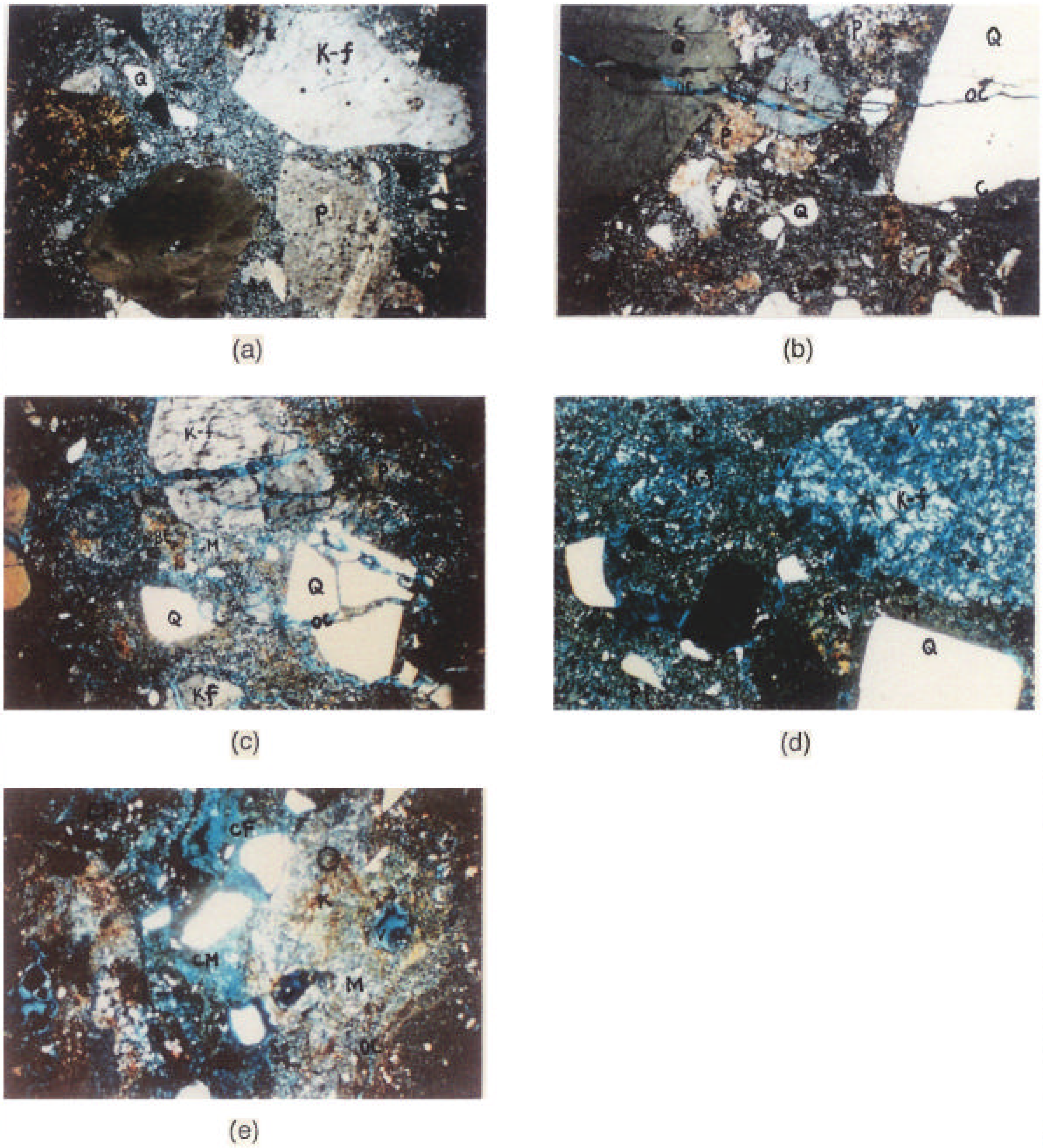
Plate 10 - Material Weathering Grades in Coarse Ash Tuff , Sai Kung



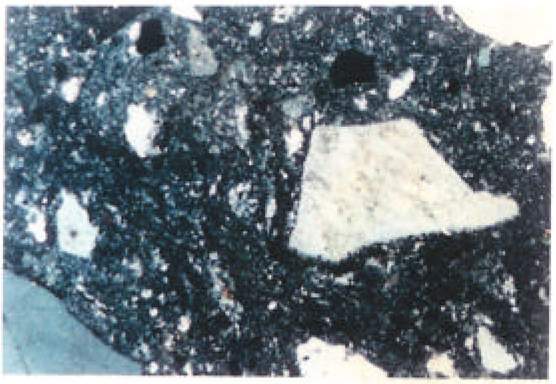
(a) Slightly decomposed tuff; (b) Moderately decomposed tuff; (c) Highly decomposed tuff; (d) Completely decomposed tuff (with honeycombed alkali feldspar, top and right); (e) Transition soil (with partially collapsed fabric, left half)

Kf - Alkali feldspar, P - Plagioclase, Q - Quartz, Bt - Biotite, M - Fine-grained matrix; oc - Open microcrack; v - Void, CM - collapsed fabric. Blue areas - epoxy resin with blue dye infilled voids and microcracks. Cross-polarized light.

Scale : length of photograph = 3.5mm

(Negative No. HQ9601706)

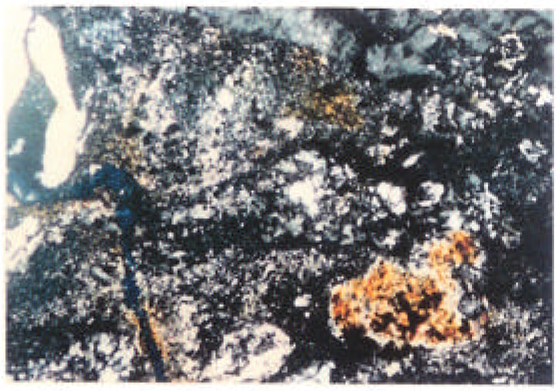
Plate 11 - Micrographs Illustrating Minerlogical and Fabric Properties of Coarse Ash Tuff Weathered to Different Degrees



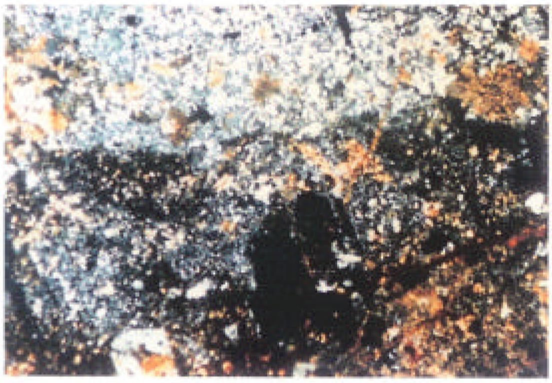
(a)

(b)

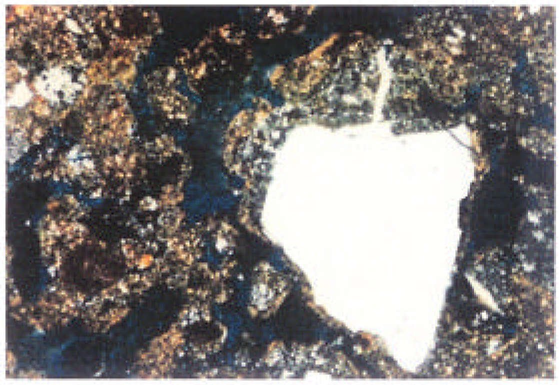
(c)



(d)



(e)



(f)

(a) Fresh fine ash tuff (ATW1); (b) Fresher portion of slightly decomposed tuff (ATW2); (c) Stained portion of slightly decomposed tuff (ATW3); (d) Highly decomposed tuff (ATW4); (e) Highly decomposed (altered) tuff (ATW5); (f) Completely decomposed tuff (ATW6).

Scale : length of photograph = 2.5mm

(Negative No. HQ9700202)

Plate 12 - Micrographs Illustrating Minerlogical and Fabric Properties of Fine Ash Tuffs Weathered to Different Degrees

APPENDIX A

SAMPLE DESCRIPTIONS

APPENDIX A : SAMPLE DESCRIPTIONS

Locality : New Slope Cutting at Ap Tsai Wan, Tseung Kwan O

Sample No.	Location	Description of Hand Specimen
ATW1 (JB8)	Sample taken from fresh rock zone near base of 50-60 m high cut.	Fresh. Very strong, dark grey, very fine grained matrix with up to 20% feldspar and occasional quartz megacrysts (max. 2 mm), occasional lapilli, fine ash TUFF.
ATW2 (JB5)	Sample taken from lower part of moderately weathered zone in cut slope, half way up the hill.	Slightly decomposed (slightly discoloured). Very strong, yellowish brown discoloured rim, up to 10 mm wide with very strong, medium grey fresh core, fine ash TUFF.
ATW3 (JB5)	Adjacent to sample ATW2.	Slightly decomposed (moderately discoloured). Strong, yellowish brown to dark brown discoloured rim, up to 20 mm wide with very strong, medium grey, fresher core, fine ash TUFF, occasional feldspars are gritty in discoloured rim; a series of tight microcracks parallel to discoloured zone.
ATW3F		Fresh Core.
ATW3W		Discoloured rim (Moderately Decomposed).
ATW4 (JB3)	Sample taken from closely jointed, highly weathered rock zone, in cut slope near top of hill (about 5-7 m below original ground surface before cutting).	Highly Decomposed. Weak to very weak, completely discoloured yellowish grey with brown and patchy black staining along fractures, fine ash TUFF; large feldspars are gritty occasionally powdery; white kaolin(?) infill (vein?), macro-fractures at 5 to 20 mm spacing.
ATW5 (JB3)	Adjacent to ATW4.	Highly Decomposed (Slightly Altered). Very weak, completely discoloured, light yellowish grey with patchy brown and black on fracture surfaces, fine ash TUFF; feldspars are gritty to powdery; kaolinized adjacent to one face; macro-fractures at 3 to 40 mm spacing.

Sample No.	Location	Description of Hand Specimen
ATW6 (JB1)	Sample taken from completely weathered rock zone in cut slope (approx. 2 m below original ground surface before cutting).	Completely Decomposed. Extremely weak, yellowish brown with pinkish orange and olive green patches, fine ash TUFF (eutaxitic?); feldspars clayey to powdery, loss of tuff fabric at places, particularly around rootlets (Clayey sandy silt).

Locality : Access Road Cutting, above Tseung Kwan O New Town

Sample No.	Location	Description of Hand Specimen
TKO1	Sample taken from fresh core of a small corestone in moderately weathered tuff zone cutting; along access road.	Fresh core of slightly discoloured block. Very strong to extremely strong, dark grey, crystal-bearing fine ash TUFF.
TKO2F	Sample taken from partially discoloured portion of above corestone.	Fresher core of moderately discoloured block. Very strong, light to medium grey (faintly discoloured) core with yellowish grey to yellowish brown rim (TKO2W), 20 mm wide, crystal bearing fine ash TUFF; black oxide coating on joint surface.
TKO2W	Same as TKO2F (discoloured rim of corestone).	Completely Discoloured (moderately decomposed) rim of TKO2. Light grey with yellowish grey to yellowish brown (on joint surface), moderately strong to strong, fine ash TUFF.
TKO3	Adjacent to TKO1, small corestone.	Moderately Decomposed. Moderately weak, light yellowish grey with reddish brown and black on joint surface, completely discoloured fine ash TUFF; some feldspars are gritty, irregular fractures at 10 to 80 mm spacing near joint surface.
TKO4	Sample taken from highly weathered rock zone along access road cutting, adjacent to TKO4.	Highly Decomposed. Weak, yellowish grey with yellowish brown on joint surfaces, patches of black, fine ash TUFF; micro-fractured throughout at 5 to 40 mm spacing. Light pink feldspars on one side of block (altered?); most large feldspars are powdery.
TKO5	Sample taken from completely weathered zone.	Highly Decomposed. Very weak, yellowish grey with reddish brown and patches of black, fine ash TUFF; micro-fractured at 10 -20 mm spacing, irregular pattern; veinlets of kaolin (altered?)(Can be crumbled to sandy silt with strong finger pressure).

Sample No.	Location	Description of Hand Specimen
TKO6	Sample taken from completely weathered zone, a few metres West of TKO7.	Completely Decomposed (very dense). Extremely weak, mottled yellowish grey and reddish brown, fine ash TUFF; all large feldspars are powdery to soft; easily crumbled to individual grains (Sandy silt with some clay).
TKO7 (S2)*	Sample taken from trial pit in transition soil zone.	Transition soil with partial tuff fabric (about 30%). Loose to dense, reddish brown and yellowish brown, fine ash TUFF (Clayey silt).
TKO8	Sample taken from residual soil zone, about 1.5 m below ground surface.	Residual soil. Reddish brown with patches of yellowish brown, small patches of tuff fabric (Clayey silt).

Locality : Landslip Site behind Island Road Government School, Aberdeen

Note : For details, see Irfan (1994)

Sample No.	Location	Description of Hand Specimen
IR1	Core sample from borehole BH1, at 9.6 m depth in highly weathered rock zone.	Slightly Decomposed (Slightly Discoloured). Strong, medium grey with light yellowish grey in the vicinity of joint surfaces, coarse ash TUFF; Megacrysts (up to 4 mm) of quartz and feldspars, in a finely crystalline matrix; biotite rich, 5 to 10%; feldspars gritty in stained rim.
IR7	Core sample from borehole BH1, at 6.5 m depth, in highly weathered rock zone.	Slightly Decomposed (Highly Discoloured). Moderately strong to strong, light grey core with yellowish grey rim (up to 4 mm wide), coarse ash TUFF; most large feldspars gritty in the discoloured rim; very closely spaced fractures parallel to joint surface.
IR2	Core sample from borehole BH1, at 8.6 m depth in highly weathered rock zone.	Moderately Decomposed. Moderately weak to strong, light yellowish grey with yellowish brown secondary staining along joint surface; coarse ash TUFF; feldspars with varying degrees of decomposition but mostly hard to gritty, except near joint surfaces they are powdery.
IR8	Core sample from borehole BH1, at 5.3 m depth in highly weathered rock zone.	Moderately Decomposed. Moderately weak, light yellowish greenish grey, coarse ash TUFF; feldspars powdery to gritty; micro-fractured by a network of irregular, branched microcracks.
IR4	Core sample from borehole BH1, at 8.8 m depth.	Highly Decomposed. Weak, light yellowish grey, coarse ash TUFF; feldspars powdery to gritty, some soft.
IR9	Core sample from borehole BH1, at 7.3 m depth in highly weathered rock zone.	Highly Decomposed. Very weak, light yellowish grey, coarse ash TUFF; feldspars powdery, some soft.

Sample No.	Location	Description of Hand Specimen
IR5	Core sample from block sample IR5 in a trial pit (TP3) at 0.3 m below landslip surface in completely weathered zone. Sample contains up to 30 mm thick kaolin veins and relict joints.	Completely Decomposed and hydrothermally altered. Extremely weak, light yellowish grey to pinkish grey (altered portion), coarse ash TUFF with kaolin veins; feldspars powdery to soft (in the vicinity of kaolin veins (clayey sandy silt). Specimens IR51 and IR55 are kaolin veins.
IR3	Block sample taken across shear plane comprising both the undisturbed saprolitic zone containing kaolin veins and creeping zone.	Completely Decomposed. Extremely weak, yellowish grey with pinkish grey and white patches, coarse ash TUFF with relict joints and kaolin veins; feldspars powdery to soft and biotite greenish grey to silvery grey (Clayey sandy silt).
IR6	Block sample taken from a trial pit, at 1.3 m depth, in residual (transition) soil zone.	Transition soil. Mottled reddish brown and yellowish grey with thin discontinuous kaolin veinlets but no relict discontinuities; partial loss of tuff fabric throughout block sample (Clayey sandy silt).

Locality : Sai Kung, Old Borrow Area

Sample No.	Location	Description of Hand Specimen
SK7 (CT5)	Sample taken from a corestone, about 3 m below original ground surface, in completely weathered rock zone.	Slightly Decomposed. Very strong, medium to dark grey fresher core with light yellowish grey rim, up to 10 mm wide, coarse ash TUFF with occasional lithic fragments and abundant quartz and feldspar crystals, up to 4 mm in diameter; feldspars gritty.
SK6	Sample taken from a corestone in completely weathered rock zone.	Slightly Decomposed. Strong, dark grey core surrounded by light grey inner rim and light yellowish grey outer core; flow-banded porphyritic LAVA with cluster of quartz and feldspars (The sample is possibly from a lava band within coarse ash TUFF).
SK5 (CT4)	Sample taken from core of a corestone, about 3 m below original ground surface, in completely weathered rock zone, 1 m to the west of SK7.	Moderately Decomposed. Weak, light yellowish grey with brown and black patches, completely discoloured, coarse ash TUFF; most feldspars gritty, some hard; occasional quartz up to 6 mm.
SK4 (CT4)	Sample taken from outer rim of the same corestone as SK5.	Highly Decomposed. Very weak, light yellowish grey, coarse ash TUFF with very closely spaced fractures; thin clay infill along some fractures; feldspars powdery to gritty, some soft.
SK2 & SK3 (CT3)	Sample taken in completely weathered rock zone, about 2 m below original ground surface.	Completely Decomposed. Extremely weak, yellowish brown with yellowish grey, coarse ash TUFF; with patchy fabric loss; most feldspars powdery to soft (Clayey sandy silt).
SK1 (CT1)	Sample taken from residual soil zone, about 0.8 m below ground surface.	Residual soil. Reddish brown, sandy clayey silt with small patches of tuff matrix; numerous pores, up to 2 mm in diameter and desiccation cracks.

Locality : Tai Tong East Borrow Area, Yuen Long

Sample No.	Location	Description of Hand Specimen
YL1	Sample taken from fresh core of a large corestone, in completely weathered rock zone, within the landslip area.	Fresh. Very strong, medium grey, lapilli bearing coarse ash TUFF with occasional sedimentary rock fragments, epidote-chlorite veined (altered), abundant feldspars (dominantly plagioclase) with quartz crystals.
YL6	Sample taken from a highly decomposed corestone, adjacent to trial pit TP1 in the landslip area.	Highly Decomposed. Extremely weak to very weak, dark greenish yellowish grey, coarse ash TUFF containing a series of parallel micro-fractures spaced at 5 mm, feldspars powdery to gritty; quartz dull, brownish stained; biotite greenish grey, powdery.
YL3	Sample taken at 1 m depth in trial pit TP1 in the landslip area, in completely weathered rock zone.	Completely decomposed. Extremely weak, light greenish yellowish grey, coarse ash TUFF; feldspars gritty to powdery, occasionally soft; quartz very dull (Sandy silt with little clay).
YL5	Sample taken at 1.5 m depth in trial pit TP4 in the landslip area, in completely weathered rock zone.	Completely Decomposed. Very dense, greenish grey with patches of yellowish grey, coarse ash TUFF; feldspars powdery, occasionally soft; quartz very dull; biotite powdery, yellowish greenish grey; groundmass powdery to soft (Clayey sandy silt).
YL4	Sample taken from deformed saprolite layer at 0.5 m depth in trial pit TP1, containing polished shears surfaces.	Deformed completely decomposed tuff. Light greenish grey with patches of yellowish brown; no relict joints but with deformed disturbed tuff fabric.

APPENDIX B

METHODS OF PETROGRAPHICAL AND CHEMICAL ANALYSIS AND IDENTIFICATION OF MINERALS

B.1 General

The chemical and XRD analyses of the coarse ash tuff specimens from the landslip site at Aberdeen were carried out on duplicate specimens at Amdel and Analabs laboratories in Australia in 1989. The mineralogical interpretations from XRD traces were carried out by Dr R. Brown of Amdel and Dr R. J. Gilkes and Mr G.D. Moore of Analabs.

The chemical analyses by XRF were carried out by Sietronics Pty in Australia on the tuff specimens from Tseung Kwan O (TK series), Sai Kung (SK series) and Ap Tsai Headlead (ATW series), which also carried out the XRD analyses on the same specimens. The XRD analyses on these rocks using duplicate specimens were repeated by Messrs S. V. Prior and S. J. Kemp of the British Geological Survey (BGS) in the U.K. due to uncertainty with some of the interpretations made by Sietronics Pty. The BGS determined the quantitative normative bulk mineralogies of these rocks using the chemical analyses results of Sietronics Pty.

The BGS also carried out the chemical and XRD analyses of the specimens from Yuen Long (YL series). The mineralogical and fabric description of all rocks were carried out by the author (T. Y. Irfan), using thin sections and hand specimens.

B.2 Methods of Analyses Used by Amdel

B.2.1 Clay Mineralogy by XRD

Portion of each sample was powdered finely and used to prepare an X-ray diffractometer trace which was interpreted by standard procedures.

Further, weighed, lightly pre-ground subsamples were taken and dispersed in water with the aid of deflocculants and an electric blender, and allowed to sediment to produce -2 μm e.s.d size fractions by the pipette method. The resulting dispersions were examined by plummet balance to determine their solids contents, and were then used to produce oriented clay preparations on ceramic plates. Two plates were prepared per sample, both being saturated with Mg^{++} ions, and one in addition being treated with glycerol. When air-dry, these were examined in the X-ray diffractometer. Additional diagnostic examinations carried out consisted of examination of the glycerol-free plate after heating for one hour at 110°C, after treatment with formamide or glycol, and after heating for one hour at 550°C (various treatments according to individual requirements). The radiation used was CoKα.

B.2.2 Chemical Analyses

Whole rock chemical analyses were carried out by Inductively Coupled Plasma (ICP) Atomic Absorption Spectroscopy.

The loss on ignition (LOI) was determined by heating representative finely ground specimens to 1300°C and relating back weight losses to original sample weights.

B.2.3 Mineral Calculations from Chemical Analyses

A suitable computer program was used for the calculation of mineral proportions using the chemical analysis results. Appropriate theoretical, or quoted practical compositions for the component minerals were used in the calculations, and in some instances these were varied slightly when the calculated fit for minor minerals (e.g. biotite, vermiculite) was poor. Minerals which were not observed by XRD were not introduced into the calculations, although in some cases this would have resulted in a considerably improved agreement. In any case, the effect on the calculated percentages of the major minerals is usually negligible. The figures given in the tables are quoted to the nearest percent, but the actual accuracy, although unknown, is not expected that level. It is possible that appreciable amorphous material (amorphous clay or volcanic glass) is present. If that is the case. the calculated mineral percentages could be considerably in error.

Iron was calculated to goethite on the basis of the observation of goethite in some samples, especially in the clay fractions.

B.2.3 Comments on Mineral Determinations by XRD

All three kaolin minerals (kaolinite, hydrated halloysite and halloysite or dehydrated halloysite) are present in many samples. There is no known method to estimate the proportion of hydrated and dehydrated halloysite by XRD. The presence of hydrated halloysite was detected from peak shift with glycerol. The approximate proportion of halloysite (including both types) in the total kaolin was estimated by formamide treatment of the clay fractions. Whether the relative proportions are maintained in the bulk sample is of course uncertain as this would depend on the grain size of kaolinite and halloysite particles in the bulk material.

Smectite was only identified in kaolin veins. In the instances where interstratified clay was identified, the clay layers making up the material were not able to be determined with certainty. An illite-vermiculite interstratification has been suggested but the evidence is not good.

Muscovite and illite merge into one another, the dividing line being indefinite and the differences being essentially those of crystallinity, potassium content, hydration and probably particle size. Because of their close relationship, the XRD results are usually reported as mica/illite or muscovite/illite. Based on diffraction peak breadths, which were generally weak, the micaceous minerals in the tuffs from Aberdeen are probably illite.

B.3 Methods of Analyses Used by Analabs

B.3.1 Bulk Mineralogy by XRD

Finely pulverised portions of each rock sample were placed in the diffractometer as loose packed randomly orientated samples using the back loading technique to reduce orientation problems. A diffractrogram was run each sample covering the angular range of 4 to 65 degrees (d spacings of 22A to 1.43A) and using Cu radiation.

Each scan was then examined using transparent overlays to identify the presence or absence of mineral species. Quantification is based on typical analyses for each type of mineral. Many minerals such as the clays and feldspars do not have set stoichiometry and therefore the data must be regarded as semi-quantitative.

B.3.2. Clay Mineralogy by XRD on Clay Fraction

Soil specimens were dispersed in a dilute alkali solution using on ultrasonic probe. The clay fraction (less than 2 microns) was collected by sedimentation and the clay coated onto the porous ceramic plates under suction. The clay was saturated with :

a. Mg solution

b. Mg-glycerol

c. K-550°C prior to XRD analysis using a Philips goniometer with diffracted beam monochromator.

B.3.3 Whole Rock Analyses by XRF

X-ray Fluorescent Spectroscopy (XRF) was used for the determination of all oxides except for Na_2O which was determined by Atomic Absorption Spectroscopy (AAS).

For the XRF analysis, the samples were prepared as glass fusion discs which reduces or eliminates the inherent effects; the glass eliminates particle size effects and partially normalises absorption effects through dilution. An accurately weighed portion of the pulverised sample was added to a preweighed amount of lithium borate flux which contained the heavy X-Ray absorber lanthanum oxide. These were carefully mixed and then fused in platinum gold alloy crucibles to produce a homogeneous melt. The molten glass was then poured onto a graphite platten and pressed out to form a solid glass disc which after cooling was presented to the XRF for analysis.

The calibration for the XRF is based on a synthetic master standard but for "fine tuning" of the data a series of certified reference materials were also prepared and run with the samples. Appropriate corrections were applied to correct for backgrounds, peak overlaps and absorption and enhancement effects.

Because sodium is not a particularly sensitive element by XRF this cation was determined by AAS using a mixed acid digest. An accurately weighed portion of the sample was digested in heated teflon beakers using perchloric, nitric, hydrochloric and hydrofluoric acids. Following dissolution the solution was made up to volume in volumetric flasks using deionised water. Analysis by AAS with calibration was based on "Volucon" standard solutions and certified reference materials used as checks.

Moisture and loss on ignition (LOI) were determined by gravimetric methods whereby weight losses at specific temperatures, 105°C for moisture and 1050°C for LOI, were recorded and related back to the original sample weights. Two of the samples TLC15 and IR39 were extremely wet and before any analyses or preparation were carried out, were dried. The results reported for these two samples are on the 'dried sample' basis. All other samples are reported on the 'as-received' basis.

B.4 Methods of Analyses Used by British Geological Survey

B.4.1 Sample Preparation

A representative 20 g portion of each sample was dried at 55°C, crushed and hammer-milled to pass a 200 μm screen. This material was used for thermogravimetric (TG) analyses. To provide a finer and uniform particle size for whole-rock X-ray diffraction (XRD) analysis, approximately 3 g of the less than 200 μm material was subsampled, wet micronised under acetone for 5 minutes and dried at 55°C.

Oriented XRD mounts were prepared from weathered samples to provide a more detailed analysis of the clay minerals present. 20 g of each sample was dispersed in distilled water using an ultrasonic probe and laboratory stirrer. The resulting suspension was then passed through a 63 μm sieve and the <63 μm portion allowed to settle in a gas jar. To prevent flocculation, 2 ml of 0.1 M sodium hexametaphosphate was added to each suspension. After a time period specified by Stokes' Law, a nominally <2 μm fraction was removed and sedimented onto a porous ceramic disc using vacuum apparatus.

B.4.2 X-Ray Diffraction Analysis

XRD analyses were carried out using a Philips PW1700 series automatic diffractometer equipped with a cobalt tube and operating at 45 kV and 40 mA. To provide bulk rock analyses, micronised powders were back-loaded into standard aluminium sample holders and scanned over the range 2-50 °2θ at a speed of 0.9 °2θ /minute. No <2 μm fraction separations were attempted from the fresh, volcanic samples YL1, TK01, TK02/1, SK7, SK6, ATW1 and ATW2 as these were considered unlikely to contain clay minerals.

B.4.3 Thermogravimetric Analysis

To provide a quantitative analysis of any 'kaolin' phase, gibbsite or goethite present, between 9 and 10 mg of the hammer-milled sample was heated in a Stanton Redcroft TG 750 thermobalance at 50°C/minute in a carbon dioxide gas stream flowing at 25 ml/minute. 'Kaolin' concentrations were calculated from the weight loss accompanying dehydroxylation between 500 and 600°C. As in the case of the <2 μm fraction separations, it was not considered necessary to analyse the fresh, volcanic samples YL1 and ATW1 as these were unlikely to contain such minerals.

B.4.4 Chemical Analysis

Major oxide chemical analyses using X-ray fluorescence, and loss on ignition determinations were carried out on the YL-group samples by the analytical Geochemistry Group, BGS.

Approximately 5 g of tema-ground sample was dried for 24 hours at 105°C. Loss on ignition was calculated from any further weight loss from 1 g of sample heated at 1050°C for 1 hour. Glass beads were then prepared by fusing 0.9 g of each sample with 9 g (corrected for loss on fusion) of Spectroflux-100 ($Li_2B_4O_7$) at approximately 1200°C (in a Philips Perl'X-2 microprocessor-controlled automatic fused bead maker) and pouring the melt into a platinum casting dish. Lithium iodide (LiI) was added to all samples before fusion to act as a releasing agent.

Samples were then analysed using a Philips PW1480/10 sequential, fully microprocessor controlled wavelength-dispersive XRF spectrometer equipped with a scandium anode tube. Analyte angles were calibrated from international and in-house standard reference materials, prepared as fused glass beads. Drift correction was catered for by an external ratio monitor and background correction was applied where necessary. Ten major elements were calibrated as oxides using the de Jongh calibration algorithm and the alpha coefficients generated empirically with one regression based line overlap (Ca on Ng). Oxide concentrations were merged with loss on ignition figures and the results totalled. No lower limits of detection are quoted for major elements but reporting limits are 0.01% for all oxides with the exception of MnO which is reported to 0.001%.

B.4.5 Mineral Quantification from Chemical Analyses

Both K-feldspar and plagioclase contents were calculated from the XRF K_2O and Na_2O figures assuming a stoichiometry of $KA1Si_3O_8$ respectively. The plagioclase concentration calculation necessarily assumes the absence of anorthite (Ca-rich) or mixed cation (Ca/Na) species. The K-feldspar concentration calculation also assumes the absence of other potassium-bearing phases such as muscovite or illite. Therefore where both K-feldspar and significant 'mica' were detected by XRD, the K_2O figure was apportioned on the basis of K-feldspar XRD peak height data. A calibration curve was constructed from the 3.30 Å K-feldspar peak data from those samples where only trace 'mica' content could then be determined. The K_2O contribution from the K-feldspar was then determined, and the 'mica' concentration calculated from the residual K_2O figure.

However, it was not possible to apply this XRD peak-height method of quantification to the 'mica' phase(s) as broadening of the 10 Å peak indicates a change in crystallinity and/or phase change during weathering.

Quartz concentrations were estimated from the residual wt% SiO_2 figure obtained after subtraction of the SiO_2 due to 'kaolin', plagioclase and K-feldspar, and 'mica' assuming that these were the only silica-bearing phases present. The hematite concentration was taken as the wt% Fe_2O_3.

The total wt% figures for quantitative phases are generally 100+/-10%. Where totals exceed this limit the sources of error are probably due to the increased concentration of non-quantified minerals, such as 'mica', chlorite, vermiculite, hydrobiotite, ?carbonates and ?titanium oxides as well as calculation errors due to the stoichiometries assumed.

B.4.6 Comments on Mineral Identification from XRD

Diagnostic testing indicates that the <2 μm fractions of the samples are composed of kaolinite with minor 'mica' and occasional halloysite, chlorite, vermiculite and hydrobiotite. The basal spacings of chlorite (14 Å) and 'mica' (10 Å) were unaffected by the tests applied but kaolinite (7 Å) collapsed at 550°C/2 hours to and to an X-ray amorphous state. Halloysite was detected by a reduction in the 10 Å peak and corresponding increase in the 7 Å peak after heating at 110°C/2 hours. A 14 Å peak, unaffected by glycolation and heat treatment to 100°C, but which collapsed to approximately 10 Å after heating to 550°C was attributed to a dioctahedral vermiculite. The presence of hydrobiotite, a regularly interstratified mica-vermiculite, was indicated by a superlattice reflection at approximately 25 Å in the air-dry trace of certain TK- and SK-group samples. This peak remains unaffected by glycolation or heating to 110°C/2 hours but collapses to approximately 10 Å after heating to 550°C.

The relatively broad basal spacing peaks of kaolinite indicate it is a b-axis disordered type or meta-halloysite.

B.5 Methods of Analyses Used by Sietronics, Australia

B.5.1 Methods of Analyses

Four suites of samples received were examined using x-ray diffraction, thin section microscopy and x-ray fluorescence spectroscopy.

X-ray diffraction scans were collected using the following instrumental conditions:

Cu K alpha radiation
45 kV 35mA tube power
1°/minute scan speed

X-ray fluorescence analyses were carried out on a Siemens SRS 300 x-ray spectrometer using an Rh anode x-ray tube, with other parameters set to optimise the particular element being measured.

Major silicate element analyses were carried out on fused discs. The method used closely followed that of Norrish and Hutton where the fusion mix contains lanthanum oxide as a heavy absorber.

Water was measured gravimetrically and carbon dioxide was analysed using a CO_2 analyser (LECO).

8.5.2 Sample Preparation

(a) Crushing

Samples were dried at air temperature. Crushing was carried out using Rocklabs swing-mill. All samples were crushed under similar conditions in order to ensure grain size etc. was consistent.

(b) X-Ray Diffraction

Unoriented powder mounts of the total sample were prepared for bulk mineralogy. Oriented sedimented mounts were made for examination of clay minerals (<2 micron fraction). These were obtained by suspension methods and air drying of the solution onto a glass slide. Scans were run of the clay untreated, and after heating to 15°C for 30 mins several scans were made after glycolation to check for the presence of smectities (negative result in all cases).