REPORT ON THE INVESTIGATION OF KAOLIN-RICH ZONES IN WEATHERED ROCKS IN HONG KONG

GEO REPORT No. 132

S.D.G. Campbell & S. Parry

GEOTECHNICAL ENGINEERING OFFICE

CIVIL ENGINEERING DEPARTMENT

THE GOVERNMENT OF THE HONG KONG SPECIAL ADMINISTRATIVE REGION

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This report was originally produced in September 2001
as GEO Special Project Report No. SPR 5/2001

First published, December 2002

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PREFACE

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. A charge is made to cover the cost of printing.

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

R.K.S. Chan
Head, Geotechnical Engineering Office
December 2002

FOREWORD

Following the landslides at Fei Tsui Road and Shum Wan Road in 1995, the Geotechnical Engineering Office instigated a series of investigations of kaolin-rich zones in weathered rocks, including engineering geological area studies, clay mineralogy and shear strength studies, and an assessment of downhole geophysical techniques. The aim of these studies was to improve practice with respect to the identification and interpretation of kaolin-rich zones. These various studies have been reported on separately in reports issued by the Geotechnical Engineering Office.

The purpose of this report is to synthesise the results of the previous studies and to summarise the state-of-the-art understanding on the subject. This is aimed at helping to promulgate the findings to the geotechnical profession and to provide readers with a convenient source of references on the work completed to date.

Preparation of this document was undertaken by S.D.G.Campbell and S.Parry, under the direction of H.N.Wong, who also reviewed the document. Y.C.Chan, W.K.Pun, K.P.Yim, and K.K.S Ho provided valuable comments and suggestions on the report. Other major contributors to the studies on which the report is based, included C.J.N.Fletcher, C.A.M.Franks and K.C.Lau. Many other GEO colleagues were also involved in the investigations.

(H.N.Wong)
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ABSTRACT

In 1995, two large landslides, at Fei Tsui Road and at Shum Wan Road, both of which caused fatalities, were influenced by kaolin-rich zones. Following the landslides, the Geotechnical Engineering Office (GEO) carried out a series of studies to improve understanding of the origin, distribution and characteristics of kaolin-rich zones in weathered rocks, which may adversely affect slope stability. The studies, of engineering geology, clay mineralogy, shear testing and downhole geophysical techniques, were completed in 2001 and have been separately documented in reports published by the GEO. They have formed the basis of Technical Guidance Notes issued by GEO to assist in identifying kaolin-rich zones.

Kaolin-rich zones in Hong Kong comprise layers within which kaolin veins and infills occur within weathered volcanic and granitic rocks, and occasionally sedimentary rocks. The kaolin infills and veins occupy discontinuities, including joints, faults, shear zones and lithological contacts. Manganese oxide and variably kaolinized highly to completely decomposed volcanic and granitic material, are common within the kaolin-rich zones. Kaolin infills also occur in some superficial deposits.

The main process controlling the formation and redistribution of kaolin in Hong Kong is weathering. Hydrothermal effects are only locally important. With respect to vertical distribution, kaolin concentrations mainly occur in relict discontinuities in saprolite (Grades V and IV material), and kaolin is usually restricted in amount in Grade III rock or better. The thickest kaolin-rich zones and kaolin infills are associated with low-angle discontinuities dipping sub-parallel to natural slopes, especially within a few metres vertically of the weathering front, (typically the upper bounding surface of PW90/100 rock mass) particularly where overlain by PW0/30 rock mass. The main lateral controls of kaolin distribution include faults and shear zones, zones of more closely-spaced discontinuities and depressions in the weathering profile, all of which may host kaolin-rich zones.

Mineralogical evidence indicates that the kaolin comprises halloysite and kaolinite in varying proportions, and is mainly transported in solution. The kaolin varies depending on whether it formed as a result of weathering or hydrothermal processes. In the case of weathering, the kaolin further reflects the primary rock-forming minerals from which the kaolin was derived, the rate at which they altered, whether shearing occurred, and whether there was drying during kaolin formation. As kaolin infills commonly show evidence of shear deformation, there may be a relationship between shearing and kaolin concentration.

Shear strength testing of kaolin infills is commonly carried out using a direct shear box. However, obtaining representative shear strength data of kaolin infills is difficult. This is due to such factors as the limited amounts of infill, the alignment of the infill during shearing and volume changes during loading. Consequently, interpretation of the data requires considerable care. The shear strength also varies due to the morphology of the two main kaolin minerals found in Hong Kong. Kaolinite, which has a typically platy morphology, tends to align during shearing, whilst halloysite, which has a tubular morphology, does not. Hence, kaolinite typically has both a lower peak and residual shear strength than halloysite.

Of the available downhole geophysical techniques assessed, gamma density and spectral gamma ray methods can be used as supplementary ground investigation techniques to help to identify weak layers, including kaolin-rich zones.

CONTENTS

1. INTRODUCTION

On 13 August, 1995, two large landslides that were land influenced by kaolin-rich zones occurred in Hong Kong. The first (Plate 1), at Fei Tsui Road in Chai Wan, released about 14 000 m^3 of debris and resulted in one fatality. The second (Plate 2), at Shum Wan Road near Aberdeen, had a volume of 26 000 m^3 and caused two fatalities. Following the landslides, the Geotechnical Engineering Office (GEO) carried out a series of studies to improve understanding of the origin, distribution and characteristics of kaolin-rich zones in weathered rocks, which may adversely affect slope stability. The studies were completed in 2001 and have been separately documented in reports published by the GEO.

This report synthesises the results of the studies and summarises the state-of-the-art understanding on the subject. This is aimed to help to promulgate the findings to the geotechnical profession and to provide readers with a convenient source of references on the work completed to date.

2. GEO'S STUDIES ON KAOLIN-RICH ZONES

2.1 Background

Previous authors have described the occurrence of kaolin in Hong Kong using various terms, often interchangeably, such as zones, infills and veins. In this report, standardised terminology has been used where possible. However, in some sections, and particularly in those reviewing older literature, the original terminology has been retained to preserve the meaning and intent of earlier reports and studies from which information has been derived.

The terminology adopted in this report includes:

(a) Infill; used for minerals deposited in pre-existing discontinuities,

(b) Veins; used for minerals deposited in discontinuities that may not have been pre-existing, and

(c) Kaolin-rich zones; used for layers within which infills or veins are concentrated.

Considerable work has been carried out previously in Hong Kong into both the type of kaolin present and its formation (Parry, 1999a). From the 1940s to the 1970s, the work focused on the in situ weathering of mainly feldspars. Notably, Brock (1943) referred to the possibility that pockets of white clay-like material may be deeper projections of a once extensive decomposed mantle.

Prior to the Fei Tsui Road and Shum Wan Road landslides, work by GEO suggested that halloysite was the first kaolin mineral produced during weathering (Irfan, 1990), and this subsequently changed to kaolinite with prolonged weathering. However, it was suggested (e.g. Irfan, 1990, 1994) that significant concentrations of kaolin, and kaolin veins in particular, were formed as a result of hydrothermal events.

Recent studies completed by GEO following the Fei Tsui Road and Shum Wan Road landslides have included:

(a) Area Studies - engineering geological area studies to identify kaolin-rich zones in existing cut slopes,

(b) Studies of Clay Mineralogy and Shear Strength Studies of material within kaolin-rich zones, and

(c) Phase 3 of the Site Characterisation Study, evaluating downhole geophysical techniques for identifying kaolin-rich zones during ground investigations.

The background of these recent studies and their main findings are summarised in Sections 2.2 to 2.5 of this report. GEO's ongoing landslide investigation studies and slope studies under the Landslip Preventive Measures (LPM) Programme have also provided useful site-specific information. This has been incorporated as appropriate in this report.

Subsequent to the Fei Tsui Road and Shum Wan Road landslides, work by GEO has mainly suggested that hydrothermal effects are only locally important and that the main process of formation and redistribution of kaolin, leading to kaolin infills and kaolin-rich zones, is weathering. In particular, field observations suggest a close relationship between the presence of kaolin-rich zones, groundwater movement and weathering (GEO, 1996a and 1996b; Campbell & Koor, 1998; Franks et al., 1998; Kirk et al., 1997; Franks & Campbell, 1998; Campbell et al., 1998).

2.2 Area Studies (1996-2001)

Following an initial review by Consultants (Phase 1: Strange, 1996) of the areas around the two fatal landslide sites in 1995, GEO conducted two engineering geological area studies (Phase 2: Campbell & Koor, 1998; Franks et al., 1999) around Chai Wan and Aberdeen respectively (Figure 1). These aimed to identify other slopes with similar lithologies (fine ash tuff, including eutaxite) and geological features to the two landslide sites. The area studies were subsequently extended (Phase 3: Franks & Campbell, 1998; Yeung & Shaw, 1999; Liu et al., 2000; Parry et al., 2001a; Law & Li, 2001) to include other areas in Hong Kong (Figure 1) and other rock types, including coarse ash crystal and granite of fine and medium grain sizes.

Observations made during the areas studies, and at other sites (landslide investigation studies and LPM) during the same period, established the following with respect to kaolin that occurs in kaolin-rich zones:

(a) The kaolin commonly forms infills, and less frequently veins, that are typically:

(i) white (7.5YR 8/4 (Munsell Color, 1998)), but can vary from pink (7.5YR 7/3 (Munsell Color, 1998)) to reddish yellow (5YR 6/8 (Munsell Color, 1998)),

(ii) 1 mm to 50 mm thick,

(iii) from less than one metre up to 60 m in lateral extent,

(iv) variable in strength from very soft to very stiff depending on moisture content, and

(v) present in most volcanic (tuff and rhyolite) and intrusive (granite, granodiorite and rhyolite) igneous rock types in Hong Kong.

(b) Typically, with respect to vertical distribution, the kaolin:

(i) forms infills in relict discontinuities in saprolite (grade V and IV material),

(ii) is thickest within low-angle discontinuities dipping sub-paralll to natural slopes,

(iii) is especially concentrated within a few metres vertically of the weathering front (typically the upper bounding surface of the PW90/100 rock mass weathering zone) particularly where overlain by PW0/30 rock mass, and

(iv) is usually restricted in amount below rockhead (Grade III rock or better; GCO, 1987), where it usually occurs as thin infills of subvertical discontinuities (Parry et al., 2000a, 2000b).

The strongly preferred distribution of kaolin-rich zones with respect to the weathering profile suggests their close spatial relationship with groundwater movement and weathering (Campbell et al., 1998, Franks et al., 1998).

Occasionally, kaolin veins, and to a lesser extent kaolin-rich zones, occur within ancient colluvial deposits of Pleistocene age. They typically do so within the matrix, and especially towards the base, of the deposits, and around some clasts (Ruxton, 1987).

(c) The kaolin is generally concentrated within joints which have various geological origins, including:

(i) stress relief i.e. sub-parallel to the topography and associated with weathering and erosion,

(ii) tectonism, typically resulting in orthogonal sets, and

(iii) cooling and contraction of igneous rocks.

Kaolin also occurs, however, in other types of discontinuities, including fractures, exfoliation fabrics, shears and geological contacts.

(d) The kaolin is commonly associated with deposits of black manganese oxide which often form:

(i) the contacts between the kaolin and the saprolite, and

(ii) where slickensides are present, as a staining to the shear surface.

These observations form the basis of guidelines for identifying kaolin-rich zones that have been promulgated by the GEO in Technical Guidance Note No. 4 (GEO, 2001). Related guidance regarding ground investigation is contained within Technical Guidance Note No. 2 (GEO, 2000a).

A further consequence of the area studies, and of the Phase 2 studies in particular, was recognition of the need to improve knowledge of the mineralogy of the kaolin-rich zones that had been identified in the field. This need was addressed during comprehensive clay mineralogy studies, the results of which are synthesised in the following section.

2.3 Clay Mineralogy Studies (1998-2001)

2.3.1 General

Prior to these studies, extensive work had been carried out on the clay mineralogy of Hong Kong rocks by various researchers (Parry, 1999a). However, the majority of this work was concerned with bulk-rock clay mineralogy. Where clay veins or infills occurred, these were commonly ascribed to a hydrothermal origin (Irfan, 1994, 1996 and 1997). Field observations during the area studies (Section 2.2) showed that concentrations of clay minerals are preferentially distributed in relation to the weathering profile. This suggests that the clay minerals were transported and deposited during weathering.

2.3.2 Mineralogical Techniques

In order to investigate the origin of clay veins and infills, a series of clay mineralogy studies was undertaken by GEO and its Consultants (CSIRO, 1999, 2000 and 2001). Given that some mineralogy techniques are not yet standardized, and that interpretation of results can be subjective, a scoping study was undertaken to determine the most suitable techniques for clay mineral identification. The scoping study (Parry & Franks, 2000) examined a range of techniques selected during an earlier literature review (Merriman, et al., 1998) and made recommendations for the most appropriate combination of these techniques in future studies. This comprised: optical mineralogy using large format slides, scanning electron microscopy (SEM) together with electron microprobe analysis to provide chemical analyses, and X-ray diffraction (XRD) with differential thermal analysis (DTA) or thermogravimetric analysis (TGA) (Parry, 1999b). The recommended techniques are further outlined below (see Parry, 1999b for further details):

(a) Optical Petrographical Analysis

Resin-impregnated, large format (75x50 mm), polished thin sections are recommended for the optical petrography. Whilst these typically take approximately one to two weeks to prepare, the resin impregnation minimizes shrinkage and disturbance of microtextures in the material. Blue dye is commonly added to the resin to aid the identification of microfractures, some of which may be generated by shrinkage during sample preparation. Optical petrography is a powerful means for interpreting weathering fabrics and products but the interpretation requires experienced personnel. It is also useful for identifying non-clay mineralogy, and for characterising textures and microfabrics. Resin impregnation allows the sample to be cut without smearing, enabling detailed examination and description of the hand specimen (Plate 3).

(b) Scanning Electron Microscope (SEM)

The saprolite petrography, including mineral composition, micromorphology, microtextures and clay mineral microfabric, can be determined by scanning electron microscopy (SEM). The image resolution is in the order of 0.01 μm. An electron gun provides the source of electrons, which are focused on the surface of the sample. As the beam hits the specimen some electrons are reflected, while secondary electrons are liberated from the sample. SEM can be used either in the reflected electrons (backscatter) mode, which can be carried out on optical thin sections and gives a two dimensional image (Plate 4a), or to record secondary electrons which generate a three dimensional image of the crystal structure (Plate 4b).

(c) X-ray Diffraction (XRD)

There is little difficulty in using XRD to identify single kaolin-group minerals in isolation. However, where kaolin-group minerals occur with other clay minerals, auxiliary treatments are needed. All crystalline minerals have unique diffraction patterns. These are converted into lattice spacing in Angstrom units. Kaolinite forms a peak at ~7 Å (Angstrom) spacing. Hydrated halloysite forms a peak at ~10 Å spacing. However, dehydrated halloysite also shows a peak at ~7 Å lattice spacing. Formamide intercalation emulates rehydration and results in expansion of the halloysite lattice and a consequent shift in the XRD peak back to ~10 Å (Churchman et al., 1984). The representative proportions of kaolinite and halloysite can then be calculated. Mica, which also shows a peak at ~10 Å, is measured after the sample has been heated. The heating results in the collapse of any hydrated halloysite to ~7 Å due to the release of the absorbed water. Consequently, the mica content, which is unaffected by heating, can be quantified. A typical XRD trace is shown in Figure 2.

It is beneficial to carry out XRD in conjunction with Differential Thermal Analysis (see below) to provide a secondary check on the proportions of kaolinite and halloysite.

(d) Differential Thermal Analysis (DTA)/Thermogravimetric Analysis (TGA)

A quantitative estimation of kaolin minerals is made by measuring the area beneath the characteristic endothermic peak at 520-560 °C. The concentrations of these minerals are then obtained from graphs of these responses for known concentrations of reference samples of the pure mineral types.

(e) Electron Microprobe/Energy Dispersive X-ray Analysis (EDX)

Either an electron microprobe or an Energy Dispersive X-ray (EDX) analysis is recommended in conjunction with a Scanning Electron Microscope (SEM). Both methods allow chemical analyses to be carried out on individual clay particles, so assisting with the identification of SEM images.

2.3.3 Mineralogy of Clay Infills and Veins

Eighteen samples of clay infills and veins from six different sites, three in granite and three in tuff, were analysed as part of the present series of studies (Figure 1). In hand specimens, the clay was either light in colour, typically white or pink (e.g. 7.5YR 8/2 (Munsell Color, 1998)), or dark, typically dark brown or red (e.g. 7.5YR 7/8 to 2.5YR 5/6 (Munsell Color, 1998)). The red and brown colours indicated the presence of iron oxides/oxyhydroxides. Other minerals, such as manganese oxides also occurred and were typically black or dark grey. The mineralogical work (CSIRO, 1999, 2000 and 2001) determined that the clay infills and veins analysed were predominantly composed of kaolin and that two types of kaolin were present; halloysite and kaolinite. These are both hydrous aluminium silicates which have a common 1:1 layer silicate structure, comprising a silica sheet paired with an aluminium sheet. In kaolinite, the paired sheets are approximately 7 Å (Angstrom, 1 Å = 10^{-10} m) thick, and are commonly stacked to form tabular or platy crystals (Plate 5a). Halloysite differs from kaolinite by containing an additional single molecular layer of water resulting in a thickness of approximately 10 Å and typically forms tubular or curved crystals (Plate 5b). Because of this layer of water, two types of halloysite occur; a hydrated form, where the water layer is present and a dehydrated layer where the halloysite has been subject to drying. Dehydration of halloysite is an irreversible process in the natural environment.

Clay minerals, including kaolin, form from the alteration of primary rock minerals by hydrolysis. Structural considerations show that, with the possible exception of micas, primary minerals cannot transform into kaolin (CSIRO, 2000). Instead, kaolin is most likely to form by the dissolution of silicates and the subsequent precipitation of kaolin from this solution. Consequently, the pseudomorphs of feldspar and mica by kaolin often observed in hand specimens of decomposed igneous rocks, are probably the result of crystallization of kaolin from solution and onto minerals which act as templates for nucleation. Therefore, kaolinization within the rock mass is likely to form from solutes supplied by the breakdown of nearby primary minerals. Kaolin infills in discontinuities probably form from solutes from the same primary minerals, but which have diffused into the discontinuities.

At two of the six sites investigated there was evidence of early hydrothermal alteration in the form of greisenisation (aggregates of quartz and white mica). Despite this, there was no mineralogical evidence for the kaolin at these sites, either within the rock mass or the infills, being of a hydrothermal origin. However, one of the other sites (Fei Ngo Shan landslide site; see below) was characterised by an unusual form of the kaolin, which comprised a series of thin, irregular veins in a boxwork structure (Plate 6a). Optical microscopy work showed randomly orientated kaolin books (Plate 6b), suggesting that the kaolin was introduced into open fractures under passive conditions. Under SEM examination, the kaolin was observed commonly to comprise thin sheets with some close packing and general interlocking (Plate 6c). Such observations are characteristic of hydrothermal kaolin (Keller, 1976).

Whether kaolinite or halloysite forms during weathering depends on environmental conditions at the time of formation and is not related to igneous rock type. Several studies (e.g. Churchman & Gilkes, 1989; Irfan, 1996; Jeong, 2000) have suggested that halloysite forms earlier and kaolinite later in the same weathering profile, with hydrated halloysite dominating the clay fraction at the weathering front, i.e. in the wetter parts of the weathering profile. Higher in the weathering profile, kaolinite becomes predominant suggesting kaolinite favours drier conditions, although kaolinite may also be formed under wet conditions where leaching is intense (CSIRO, 1999). The location of kaolin formation and the type of kaolin formed depend on the rate of supply of solutes, the residence time of the solutes at the location of formation and the continuing availability of a source of solutes (CSIRO, 2000).

In addition to kaolin, a number of secondary minerals were also present at the sites investigated, including manganese oxides, iron oxides/oxyhydroxides (principally goethite), smectite and illite-smectite. All of these secondary minerals were only identified in small concentrations (typically < 2%), with smectite concentrations in particular being < 1% (CSIRO, 2000). Where they occurred contemporaneously with the kaolin, these secondary minerals appeared to have restricted kaolin growth and influenced the morphology of the kaolin minerals (CSIRO, 1999). As kaolinite typically forms in drier environments, it was more commonly observed in association with secondary oxides than the halloysite. The oxides often permeated from relict discontinuities and stained adjacent minerals (Plate 7a).

Where hydrated halloysite was present, manganese oxide and iron oxides/oxyhydroxides were generally absent, reflecting the wet environment of formation and the lack of oxidising conditions. However, where manganese oxides occurred within hydrated halloysite infills, they were usually associated with later relict, often slickensided discontinuities. The discontinuities enabled rapid drainage and oxidation to occur. The halloysite crystals in these regions were typically shorter and more platy than elsewhere, suggesting that the manganese was a constraint to further halloysite development and as a result, kaolinite formed. This interpretation was supported by the manganese oxide staining having being constrained to the immediate zone of shearing (Plate 7b) (CSIRO, 2000).

White kaolin infills were typically well crystallised and monomineralic, suggesting their formation in open, chemically clean, discontinuities. If shearing occurred, it was generally of limited extent and little incorporation of minerals from the surrounding rock into the infills was evident.

Dark infills, containing secondary minerals such as iron oxides, tended to contain similar proportions of kaolinite and halloysite, which were both small in size, and included primary minerals reflecting brecciation. This suggests that they originated as primary shear fabrics or, more commonly, were areas that were sheared subsequent to infilling. The exception to this was the kaolin veins at the Fei Ngo Shan site, which were considered to have a hydrothermal origin and which had white monomineralic infills comprising small crystals. This further indicated its different mode of genesis from that of other forms of kaolin investigated.

Both white and dark kaolin commonly showed evidence, both in the field and in thin section, of previous deformation, including shearing, brecciation and folding, with multiple generations of kaolin involved (Plate 8 (a) - (f)).

In summary, the results of the study indicate that;

(a) the kaolin formed by precipitation from solution,

(b) with the exception of one site, kaolin formation was related to weathering rather than hydrothermal activity,

(c) halloysite occurred first in the weathering profile under wet conditions,

(d) if halloysite dried out, it irreversibly dehydrated,

(e) kaolinite occurred higher in the weathering profile, and under drier conditions, than halloysite,

(f) white kaolin tended to be monomineralic,

(g) dark kaolin tended to contain similar proportions of halloysite and kaolinite,

(h) oxides tended to restrict kaolin growth, and

(i) kaolin infills were commonly sheared.

The widespread evidence of shearing suggests that there may be a relationship between deformation and kaolin formation. If repeated shearing occurs, this may result in a change in permeability and associated leaching which leads to kaolinite being formed rather than halloysite. Furthermore, if shearing incorporates primary minerals into the infill, their weathering will lead to the production of iron oxides/oxyhydroxides, imparting a red-brown colour to the kaolin.

2.4 Shear Strength Study (1998-2001)

A number of authors have reported the influence of clay mineralogy on shear strength. Wesley (1977) noted that residual soils in Indonesia have higher residual strengths than European sedimentary soils with comparable plasticity indexes. Wesley attributed this limited drop in strength towards residual strength to the presence of halloysite which, because of its tubular nature, restricts its ability to become orientated (and so reduce strength). Skempton (1985), when considering the effects of clay particle re-orientation during shear, noted that for non-platy minerals, such as halloysite, the residual strengths of such soils “bear little if any relation to the content of clay-sized particles and are usually greater than 25°”. Whilst some of the halloysite examined in this study was aligned (Plate 5b), this was considered to be the result of water flow rather than shearing. In comparison, Rossato et al. (1992), noted that kaolinite-based artificial model soils tend to orientate easily during consolidation and shear and that kaolinite has an “abnormal readiness to develop residual shear surfaces” and “the tendency of kaolin(ite) to quickly develop polished failure planes during shear is well established”. This is shown in Plate 9 where kaolinite platelets have apparently re-orientated due to shear. Rossato et al. (op. cit.) reported that once localised failure has commenced, relative displacements across shear bands as small as 2 mm may be sufficient to reduce the frictional strength to about 12°. Similarly, Anon (1997) quotes peak strength for kaolinite and halloysite as 22 to 30° and 25 to 35° respectively as compared with residual strengths of 12 to 18° and 25 to 35° respectively.

A considerable amount of shear strength testing has been carried out in Hong Kong, associated with slope failures involving kaolin. However, there are few data currently available concerning the relationship between shear strength and kaolin mineralogy in Hong Kong (Koor et al., 2000). A selection of the available data is shown in Table 1.

During the study, a number of difficulties were encountered during the testing of kaolin-infilled discontinuities (Chung, 1999). These included: time-consuming preparation, limited thickness of infill resulting in shearing of saprolite rather than infill, volume changes on the application of vertical loading resulting in the infill becoming out of phase with the plane of shearing, tilting of the top cap during shearing, and difficulty in aligning the plane of infill with the plane of shearing because the relict joints were often curviplanar. Consequently, interpretation of results required considerable care. Furthermore, the clay infills were heterogeneous, with varying clay mineralogy (i.e. halloysite to kaolinite ratio), the presence of coarse fragments in the infill, structures e.g. shear surfaces, and variable moisture content.

In order to avoid these problems, and to study the effect of kaolin composition on shear strength, commercially available samples of both halloysite and kaolinite were tested (GEO, 2000c). Direct shear tests were carried out to ascertain the peak strength and ring shear tests were used to obtain residual strength. Five kaolinite-halloysite combinations were tested: 1:1, 1:3, 1:9, 100% kaolinite and 100% halloysite.

The peak shear strength of halloysite was $c' = 0$ kPa, $\phi' = 30°$ with a residual strength of c' = 0 kPa, ϕ' = 21°. For kaolinite, the peak shear strength was c' = 0, ϕ' = 22° with a residual strength of c' = 0 kPa, ϕ' = 14°. For combinations of kaolinite and halloysite, there was a noticeable drop in strength once the kaolinite content exceeded 10% (Parry et al., 2001b) (Figure 3). The difference between the peak and residual shear strengths for halloysite is larger, however, than that reported in the literature. It is possible that the manufacturing of the commercial halloysite, especially drying and grinding, could have affected the original morphology. Also, artificially constituted halloysite and kaolinite do not replicate the structure of naturally occurring infills of the same mineralogy. These factors may have influenced the lower residual shear strengths obtained, compared to those in the literature.

2.5 Site Characterisation Study - Phase 3 (1997-2000)

A study was undertaken to evaluate the capabilities and practicality of downhole geophysical techniques to identify weak layers (including kaolin-rich zones) during ground investigations. This study was included as part of the Site Characterisation Study (SCS), a wide-ranging study of geophysical applications to geotechnical problems in Hong Kong. The downhole geophysical assessment, designated as Phase 3 of the SCS, aimed to evaluate the capabilities and practicality of a number of downhole geophysical methods to identify weak layers in the ground. This was carried out in Stages 1 to 4.

Stage 1 involved a literature review of existing downhole geophysical methods used for ground investigation (Lau, 1998). Based on this review, it was determined that the methods to be assessed during the study should include the gamma density method, spectral gamma ray method, neutron porosity method, self potential method, acoustic borehole televiewer method, 4-arm dipmeter method, 3-arm caliper method and electrical cylinder method.

Stage 2 involved the determination of geophysical material properties and was carried out by Consultants (Chan & Chen, 1999). This involved the integration of geophysical and radiometric surveys at 5 selected sites in Hong Kong.

Stage 3 (Lau & Franks 2000a) evaluated the practicality, limitations and accuracy of the selected downhole geophysical methods, based on Stages 1 and 2, in determining, under a controlled environment, the location of weak clay-rich layers of known thickness. This involved the design and construction of three calibration test pits, and the evaluation of selected geophysical equipment in the test pits. Stage 3 obtained promising results using the gamma density and spectral gamma ray methods in particular.

Stage 4 (Lau & Franks, 2000b) extended the study to four field trials, where the borehole televiewer, spectral gamma ray, gamma density, neutron porosity and electrical cylinder methods were further evaluated. It was concluded from the Stage 4 study that the gamma density and spectral gamma ray methods are the most useful (Figure 4), and their use was recommended as supplementary ground investigation techniques to help identify weak layers in the ground. This recommendation was further promulgated in Technical Guidance Note No. 3 (GEO, 2000b).

The principle of the gamma density method is to irradiate the target material with medium-high energy collimated gamma rays and to measure their attenuation between the tool source and the detectors. The attenuation (Compton scattering) is a function of the electron density of the formation that in turn is very closely related to its mass density. Based on the relative density contrast between target materials, the technique can be used, within a drillhole, to identify clay-rich zones at a practical logging speed of 1 m/min. In addition, other weak layers, including weathered seams and disturbed zones, were also identified due to their comparatively lower mass density. The resolution of the method increases with the increase in relative density contrast between the target and the adjacent materials. The resolution decreases if casing is used and as the dip angle of the weak layer becomes aligned with the drillhole axis (i.e. more vertical in a vertical drillhole).

The method is most suitable for use in uncased or plastic-cased drillholes and where the relative density contrast between the target (weak layers) and adjacent materials is high. However, caution needs to be exercised in interpreting the data as the absence of a strong signature does not necessarily confirm the absence of weak layers in the ground.

The spectral gamma ray method is based on the principle that decomposition of potassium bearing minerals leads to a progressive loss of potassium ions (K). Naturally occurring potassium contains radiogenic K. Thus, the amount of radiogenic K present in the material is related to the degree of decomposition of potassium bearing minerals in the parent rock and hence the degree of decomposition of the rock. The spectral gamma ray method produces a log of the potassium count rate along the drillhole.

The location along the drillhole where the count rate shows a significant reduction compared to the adjacent materials can be interpreted as a more weathered, and hence, weak layer. However, interpretation of the data is dependent on the origin of the target material, which may significantly affect the potassium count rate. For instance, where a clay layer does not originate directly from the decomposition of the adjacent materials, the potassium count rate of the layer may not necessarily be lower than those of the adjacent materials. Also, if thin layers are to be identified, a slow logging speed will be required, e.g. 0.05 m/min for a resolution of 50 mm.

This method does not require the use of a radioactive source and it can be used in drillholes lined with different casing types. Also, it is much cheaper than the gamma density method. The spectral gamma ray method, when applied to materials of the same origin, and preferably backed up by site-specific calibration, can give an indication of the degree of weathering.

3. SELECTED CASES

3.1 General

The characteristic features, and symptoms, of kaolin-rich zones are illustrated by the following case histories, which are derived from the area studies, from forensic and detailed landslide investigations, and from studies undertaken as part of the LPM Programme.

The cases have been selected principally to illustrate:

(a) landslides that have been influenced by occurrences of kaolin-rich zones,

(b) sites that demonstrate the nature and principal geological controls of distribution of kaolin-rich zones, and

(c) sites from which key mineralogical and shear strength data on kaolin-rich zones have been obtained.

It is intended that the cases will help to illustrate different types of kaolin-rich zones that have been observed in Hong Kong and assist geotechnical practitioners in identifying similar materials that may affect slope stability.

3.2 Fei Tsui Road Landslide (1995)

The Fei Tsui Road Landslide (GEO, 1996a; Knill, 1996a; Kirk et al., 1997) occurred in a 70° soil and rock cut-slope above Fei Tsui Road in Chai Wan. The failure occurred along a 50-60 m long section that was about 15 m deep.

The slope comprised slightly contact-metamorphosed, lapilli-bearing, fine ash vitric tuff that was variably decomposed both laterally and vertically (Figure 5). Eutaxitic foliation dipped at 10 to 20°, almost directly out of the cut-slope. A pale yellowish-white, sheared kaolin-rich zone also dipped at 10 to 20° directly out of the cut slope (Plate 10) and comprised highly to completely decomposed tuff containing kaolin, both within common veins and disseminated within the tuff and locally forming up to 70% of the material. This zone, which daylighted in the cut face after slope formation (Plate 10), controlled the surface of rupture of the landslide in the east.

In the central and eastern parts of the landslide, the kaolin-rich zone occurred within moderately to highly decomposed volcanic rock (PW50/90 rock mass), was relatively thin (0.5 m), highly kaolinized with very abundant kaolin veins, and was intimately associated with the surface of rupture. West of the failure, the zone occurred within completely decomposed volcanic rock, was more “diffuse”, relatively thick (3 m), less intensely kaolinized, and predominantly of highly to completely decomposed volcanic rock, with some moderately decomposed volcanic rock. Kaolin veins, variably lensoid, were less abundant, and most occurred near the top of the zone. Microtextures indicated multiple phases of kaolin formation (Merriman et al., 1996), manganese oxide deposition and deformation within the altered layer. These kaolin lenses and veins are thought to have been deposited during weathering, but the shear zone that localized the kaolin development may have been ancient.

Direct shear tests carried out on remnants of the kaolin-rich zone recovered at the base of the landslide showed that the shear strength of the kaolin-rich zone ($c' = 0$ kPa, $\phi' = 22\text{-}29°$) was much lower than the adjoining weathered tuff ($c' = 10$ kPa, $\phi' = 35°$) (GEO, 1996a).

A transient perched water table may have developed on top of the relatively impermeable kaolin-rich zone during the heavy rain prior to the failure (GEO, 1996a).

It was concluded (GEO, 1996a; Knill, 1996a) that the principal factors that influenced the landslide were the presence of the laterally extensive, weak and impermeable kaolin-rich "tuff layer" (kaolin-rich zone). This enabled development of a deep translational failure mechanism, and an increase in groundwater pressure after prolonged heavy rainfall that caused a perched water table to form above the "altered tuff layer". Several small failures that pre-dated the major failure in 1995 had surfaces of rupture coincident with the kaolin-rich zone.

3.3 Shum Wan Road Landslide (1995)

The Shum Wan Road Landslide (GEO, 1996b; Knill, 1996b; Kirk et al., 1997) comprised a concave surface of rupture in the upper part of the scar, related to rotational detachment and disaggregation of mainly in situ material up to 15 m thick that was deposited mainly on the lower slope. The surface of rupture in the lower slope was planar and subparallel to the slope, and associated with translational displacement of semi-intact slabs.

The site mainly comprised eutaxitic, variably lapilli- and block-bearing fine ash vitric tuff with up to 10% of coarse ash crystals. Some fiamme (tens to hundreds of mm in size) were kaolinized. Contact metamorphism pre-dated kaolin development (Merriman & Kemp, 1995).

The eutaxitic foliation on the landslide scar dipped much more steeply (70 to 90°) than in the surrounding area (15 to 40°) and had a similar strike to the axis of the landslide scar. The steep foliation zone was interpreted as a shear zone with a fault along its northern limit, separating rock (PW90/100 rock mass weathering zone) to the NNE from soil (PW30/50 rock mass weathering zone) to the SSW. Extremely to very closely- and closely-spaced joints occurred within the zone of steep eutaxitic foliation. Elsewhere, this joint set was closely- to widely-spaced. Shallowly-inclined (20 to 35°) stress release joints, dipped in the same direction as the prevailing slope and the landslide surface of rupture.

Close below the surface of rupture, joints were generally coated with manganese oxide and commonly, but variably, infilled with white and buff kaolin up to 20 mm thick. Sporadic, fissure-like joint infills of soft, moist, buff, sandy kaolin, were up to 230 mm thick, but tapered sharply downwards (Plate 11). These deposits also occurred in shallowly-inclined joints. In places, tabular fragments of white kaolin, detached from adjacent joint walls, occurred within buff kaolin which resembled that along and at the surface of rupture. The complexity of joint infills implied that protracted minor movements caused repeated openings of joints that were then infilled, physically with, or chemically by precipitation of, kaolin and manganese oxide.

Weathering depth and abundance of kaolin-filled joints were both greater at the landslide site than to its north and south. Kaolin-filled subvertical and shallowly inclined-joints, up to tens of mm thick, were common just below the surface of rupture in the upper part of the site but were rarely seen in joints in adjoining road sections which were mostly in Grade III or better rock.

The surface of rupture was associated with shearing along and between one or more planes, in a relatively thin kaolin-rich zone (up to 350 mm thick, but usually < 100 mm). This comprised (Figure 6) the following:

(a) soft, moist, buff and brown, mottled sandy silt/clay (mainly kaolin) c.10 to 100 mm thick, (max. 350 mm), containing subangular sand and gravel (slightly to highly decomposed tuff), with shear planes subparallel to the underlying kaolin layer (b), or undulose, sigmoidal and irregular, due to rotation during downslope movement. The buff clay development reflected repeated movement, and invaded brecciated areas incorporating in the process fragments of altered tuff. In addition, micro-textures indicated complex disruption in the clays, which were predominantly comprised of kaolinite (CSIRO, 2000).

(b) soft, moist, white kaolin, up to 15 mm thick, above a manganese oxide-coated, moderately-inclined joint. Kaolin appeared to have accumulated in situ, and was thickest where the joint was offset (up to c.20 mm) across sheared subvertical joints (Plate 11). Slickensides and sigmoidal shear fabrics (S-c fabrics) were consistent with downslope movement of overlying material. The kaolin contained sheared manganese oxide, subangular, fine sand of decomposed tuff; and tabular white kaolin fragments. Minor, white kaolin infills occurred within discontinuities in the underlying tuff, which predominantly comprised halloysite (CSIRO, 2000). These were locally dislocated and partly incorporated within the brown clay.

It was concluded (GEO, 1996b, Knill, 1996b) that the presence of a "clay seam" (kaolin-rich zone) along part of the landslide surface contributed to the scale and form of the landslide. Direct shear testing of the brown clay gave $c' = 8$ kPa, $\phi' = 26°$, and of slickensided brown clay gave $c' = 0$ kPa, $\phi' = 21°$ (GEO, 1996b). Persistent seepage from a "clay layer" in the southeast of the site indicated the presence of perched water. Other geological factors possibly influencing the landslide included (Kirk et al., 1997):

(a) shallowly-inclined stress release joints and associated shearing due to downslope movement,

(b) extensive, irregular kaolin infill of joints near the original ground surface, related to soil profile development and possibly recurrent coeval movement near surface, and

(c) a deeply weathered zone, coincident with a zone of faulting and subvertical eutaxitic foliation, which concentrated downslope movement of ground water.

3.4 Sai Sha Road Landslide (1998)

Two landslides occurred on 9 and 10 June 1998 on a 20 m-high cut slope adjacent to a highway, and formed within completely decomposed coarse ash crystal tuff. Within the saprolite, a well-defined relict orthogonal joint set with kaolin infill (Figure 7) up to 30 mm thick was present. The contact between kaolin infill and saprolite was often very diffuse, suggesting that the kaolin penetrated the saprolite from the vein and that the jointing extended, or even formed, during weathering (Plate 21). Slickensides were common within the relict joint infills. These surfaces were also commonly stained with manganese oxide. Corestones also influenced the development of the kaolin infill with kaolin forming concentric bands around the corestones (Plate 12). The bands reflected the former limits of the corestones, which decreased in size with time. Therefore, the innermost bands were the most recent kaolin developments, and the outermost bands were in general the oldest kaolin developments. The clay infill predominantly comprised kaolinite. There was evidence of shearing in both hand specimens and thin sections (CSIRO, 1999).

The shear strength of the kaolin-infilled joints was assessed by direct shear box tests. However, the results ($c' = 26.6$ kPa, $\phi' = 25°$) were not considered representative due to volume changes during shearing and difficulty in aligning the relict joints with the plane of shearing (Fugro Scott Wilson Joint Venture, 1999a). The setting of the direct shear test was subsequently modified by using gypsum to mount the specimen in the shear box to ensure that the shearing would occur essentially along the relict joint. The second tests showed considerable scatter, which was attributed to the variability of the shear strength along the relict joint. Assuming $c' = 0$, the average, upper bound and lower bound shear strength parameters were estimated to be $\phi' = 19°$, 30° and 10° respectively (Fugro Scott Wilson Joint Venture, 1999a).

3.5 Fei Ngo Shan Landslide (1998)

A major landslide (c.2500 m^3) in June 1998 in a cut slope at Tate’s Ridge, Fei Ngo Shan Road, Kowloon, involved failure up to 5 m below ground surface (Fugro Scott Wilson Joint Venture, 1999b). The slope comprised mainly completely decomposed, hornfelsed (thermally metamorphosed) crystal and lithic tuff and interbedded siltstone. The slope is probably underlain by fine-grained granite, so explaining the hornfelsing, and suggesting also that the tuffs were hydrothermally altered.

Kaolin veins and some kaolin-infilled relict discontinuities were locally common in the massive, predominantly completely decomposed coarse ash crystal tuff (Plate 13). In general, the veins dipped into the slope (c.43°). They were typically white, generally < 3 mm thick (max. 10 mm), and were slightly more halloysitic (55 to 65%) than kaolinitic (CSIRO, 2000). The surrounding adjacent saprolite was more kaolinitic than halloysitic. Some veins occurred along a vague primary layering, while others occurred as subparallel veins, possibly in two sets, oblique to this layering. Occasional ladder veins and boxworks were developed (Plate 6), suggesting hydrothermal genesis of the veins. This was supported by mineralogical analysis (CSIRO, 2000). Manganese oxide commonly lined the margins of the kaolin veins, but this may be a more recent product of weathering.

Although the kaolin veins did not directly control the surface(s) of rupture, their abundance is likely to have reduced the mass strength of the saprolite. In addition, kaolin from veins which intersected the surfaces of rupture was sometimes smeared along the rupture, so influencing its shear strength. The kaolin-infilled joints that dipped into the slope were locally sheared during toppling failure, producing slickensides plunging down-dip on some kaolin infills.

3.6 Shek Kip Mei Landslide (1999)

Significant distress occurred in Slope No. 11NW-B/C90 at Shek Kip Mei in August 1999 resulting in the permanent evacuation of three housing blocks. The slope comprised mainly completely decomposed medium-grained granite with corestones and coreslabs of slightly to moderately decomposed material. The distress occurred in two zones, respectively the Northern and Southern distressed zones.

In the Southern Distressed Zone, the basal surface of rupture, a planar slip surface with maximum horizontal displacement of 100 mm (Plate 14), was observed (Fugro Maunsell Scott Wilson Joint Venture, 2000) within a discontinuity, dipping variably between 10 and 30° out of the slope. The discontinuity was infilled mainly with polished, slickensided white halloysite and dark brown manganese oxide deposits (Plate 15) (CSIRO, 2000). The kaolin infill was only up to 15 mm thick. However, of considerable significance, the infill was proven to extend continuously for up to 60 m laterally. The infilled discontinuity split locally into several discontinuities within a zone up to 1 metre thick. Seepages were observed along the feature. Up to 3500 m^3 of material was displaced and the maximum depth of the displaced/distressed groundmass was estimated as about 6 metres. In the vicinity of the surface of rupture, the host lithology, originally dominated by quartz, alkali feldspar, subordinate plagioclase and lesser biotite was kaolinized by weathering, but still contained numerous relict crystals of quartz and feldspar.

Up to 1 metre of lateral movement occurred within completely decomposed granite in the Northern Distressed Zone. The basal surface of rupture at the toe of the slope was typically planar and occurred within a relatively uniform layer, about 10 mm thick, of moist, soft, dark grey silty clay comprising mainly kaolinite (CSIRO, 2000). The silty clay layer may have originated as an infill of a discontinuity, about 150 mm above slightly to moderately decomposed granite within the PW0/30 rock mass weathering zone. Seepages were observed directly above the silty clay layer and other subparallel shear surfaces were also observed (Fugro Maunsell Scott Wilson Joint Venture, 2000).

The shear strength of the kaolin along the basal surface of rupture in the Southern Distressed Zone was assessed by direct shear box tests, modified by mounting the samples in gypsum to ensure shearing along the infill. Shear strength parameters of $c' = 0$ kPa and $\phi' = 20°$ were obtained (Fugro Maunsell Scott Wilson Joint Venture, op. cit.)

3.7 Siu Sai Wan Estate

Kaolin-rich zones at Siu Sai Wan Estate (Campbell & Koor, 1998), where the cut slopes are currently being upgraded, were observed near a relatively planar rock mass weathering zone interface between the PW0/30 and PW90/100 rock mass weathering zones (Plate 16). Such zones often occur preferentially at, or immediately above, the interface. Kaolin is common within joints in the PW0/30 rock mass above the weathering zone interface, and particularly those subparallel to the interface. However, significant kaolin infills were not observed more than two metres below the interface in any of the extensive rock cut slopes (PW90/100 rock mass) alongside the estate. Although the transition from the PW0/30 to PW90/100 rock mass weathering zone is often abrupt and planar on a local scale, across the estate as a whole, marked variations are seen in the depth at which the transition occurs. For example, at a northeast-trending fault that can be traced as a photolineament towards the southwest, the weathering transition steps upward to the southeast across the steeply northwest-dipping fault. This fault-related feature is seen clearly in photographs taken during development of the slope (Plate 16). Where the weathering transition is locally upwardly convex, significant seepage occurs, but seepage is more generally associated with the transition. Vegetation in general is concentrated at, and above the transition.

As the kaolin is largely restricted to the PW0/30 rock mass weathering zone, its formation is inferred to be associated with weathering. Although the kaolin concentration at the interface tends to be inclined in the same direction as the topography of the natural slopes above the cut slope at Siu Sai Wan, in detail there is increasing variance in the case of relatively deeper occurrences associated with inclined faults. The possibility that some concentrations of kaolin were formed as a result of hydrothermal alteration, associated with faulting, cannot be ruled out.

Plate 8A in Geoguide 3 (GCO, 1988; of an excavation at Siu Sai Wan; P. Strange pers. comm.) (Plate 17) shows a similar geometry to that described above, with an abrupt interface between the PW0/30 and PW90/100 rock mass weathering zones being accompanied by the presence of what appear to be white kaolin veins within the PW0/30 zone and subparallel to the interface.

3.8 Tiu Keng Leng

During site formation in a benched 80 m high cut slope, formed as part of a major housing development at Tiu Keng Leng, it was observed (Parry et al., 2000a) that the second highest bench locally comprises completely decomposed, medium-grained greisenised granite beneath a coreslab (laterally extensive, sheet-like corestone) of Grade II/III rock. Below this bench, the slope comprises Grade II/III rock, which extends to the base of the slope. Kaolin is generally restricted to the completely decomposed granite, where it infills laterally persistent (locally >10 m) discontinuities which dip out of the slope at 19 to 34° (Plate 18). The maximum thickness of infill is 50 mm. Infills are generally sub-parallel and have sharp contacts with saprolite. Two types of infill were observed: soft to firm reddish yellow silty clay, with an apparent laminated fabric, which typically occurs close to the base of the coreslab; and a very soft pale pink mottled white clay (Figure 8). Within both the pink clay infill, which is mainly hydrated halloysite, and the reddish yellow clay, which is composed of approximately equal amounts of kaolinite and halloysite, there was evidence of several episodes of movement including brecciation (brittle) and later shearing (ductile with S-c fabrics) with at least two generations of kaolin involved in the kaolin infill (CSIRO, 1999).

In the predominantly Grade II/III rock below the bench, the laterally persistent discontinuity set that dips out of the slope was seen to be locally infilled by up to 30 mm thick of light brown sandy silt/clay material with angular clasts of white clay (Plate 19, Figure 8). This appears to be a matrix-supported sedimentary breccia, the material within which was transported by groundwater through, and deposited within, the open, weathered joint system, and through selectively eroded pipes in particular. The white clay (kaolin) clasts are interpreted as having been eroded from a kaolin-infilled discontinuity located elsewhere in the weathered rock mass.

3.9 Cut Slope No. 11NW-A/CR9, Kwai Chung

A kaolin infill was encountered during investigation under the LPM Programme in 2001 of registered cut slope No. 11NW-A/CR9. The infill was of limited extent, giving the appearance of a "pocket" of clay that had been left behind when the slope was formed, and at which time it had also failed on a large scale.

The kaolin infill was approximately 150 mm thick and was overlain by fill (Plate 20). The appearance of the kaolin was very similar to that of the "buff clay" at the Shum Wan Road landslide in 1995. The basal surface of the infill was bounded by Grade III rock, and the contact was probably a sheeting joint which was undulose and dipping at 15-55° out of the cut slope. The main body of the infill was reddish yellow (7.5YR 7/8 (Munsell Color, 1998)), streaked red (7.5YR 5/6 (Munsell Color, 1998)). Near its basal contact, the kaolin contained many clasts (up to 10 mm in size) of pink (7.5YR 7/3 (Munsell Color, 1998)) clay. A large (50 x 150 mm) sigmoidally-shaped clast of completely decomposed granite was also present along the basal surface of the infill and this was also surrounded by clasts of pink (7.5YR 7/3 (Munsell Color, 1998)) kaolin. Several discrete shear surfaces were visible in the reddish yellow kaolin. As at the Shum Wan Road landslide, the basal, light-coloured kaolin was predominantly halloysite in composition and the reddish yellow kaolin was predominantly kaolinite (Applied Geosciences Centre, 2001).

3.10 Other Cases

(a) Junk Bay Road, Kwun Tong

A 1300 m^3 failure occurred on 31 May 1982 in a cut slope on Junk Bay Road (GCO, 1982). The failure was within completely decomposed granite with rockhead a few metres below the failure scar. Two continuous daylighting joints, infilled with up to 30 mm of kaolin, dipping at 24° and 30°, controlled the lower part of the failure. Both joints were associated with significant seepage and slickensides were evident in the kaolin. Direct shear testing was carried out both on intact kaolin joints and an "artificial joint" reassembled from kaolin taken from the failure surface. The results were also compared with a single multistage direct shear test carried out for the North Point Rock Slope study (Hencher & Richards, 1982). It was concluded (GCO, 1982) that $c' = 7$ kPa and $\phi' = 27.5°$ is "probably conservative for kaolin joints".

(b) Tin Wan Hill, Aberdeen

Irfan (1986) reported on the mode of failure of a landslide at

Tin Wan Hill, Aberdeen, which occurred in August/September 1985. The rock at the site comprised fine ash tuff with, in parts, eutaxitic fabric. Three dominant joint sets with “white clayey veins presumably of kaolin up to 10 mm thick” were present. These veins were mainly concentrated in the central section of the slope where a number of fault zones crossed it.

Irfan (op. cit.) suggested that the kaolin resulted from hydrothermal alteration related to a granitic source at depth. The hydrothermal alteration was also considered to have made the rock “more susceptible to chemical weathering”. However, he did note that “very few of the kaolin veins were observed in the rock exposures to the north of the slope”. The transition from a completely and highly weathered rock mass to a slightly weathered rock mass was regarded as being very rapid. Furthermore, the approximate boundaries of the rock weathering grades and the colluvium interface were all parallel to each other, dipping at 20 to 30° out of the slope, and approximately parallel to the original ground surface. This general pattern was however broken along the shear zones where deeper weathering occurred in the bedrock. A re-examination of the drillhole records reproduced by Irfan shows that the kaolin was generally restricted to Grade IV/V material and where it did occur in Grade III or better, it was limited to thin infills in subvertical joints. This distribution suggests that the kaolin formation may have been related to weathering rather than hydrothermal alteration.

No triaxial testing was carried out but back analysis, assuming no positive pore water pressure, gave lower bound values of $c' = 0$ kPa and $\phi' = 26°$.

(c) Cho Yiu Estate, Tsuen Wan

On 30 July 1987 a failure, involving 1200 m^3 of material, occurred in a cut slope at Cho Yiu Estate, Tsuen Wan (Siu & Premchitt, 1988). The geology comprised coarse-grained granite intruded by fine-grained granite. The latter was preferentially weathered and kaolin was evident along the joint planes near the contact with the fine-grained granite. The failure was structurally controlled to a large degree by a joint set dipping at 20 to 50° which daylighted in the cut slope and a second, near vertical set parallel to the cut slope. The geometry of the failure surface was considered similar to rockhead (PW0/30 to PW90/100 rock mass weathering zone transition). In the back analysis, $c' = 0$ kPa and $\phi' = 31.5°$ were adopted for the upper part of the failure, which occurred along clay-infilled joints, based on triaxial testing on specimens containing clay infill.

(d) Island Road School, Aberdeen

Irfan (1989) reported on a landslide in 1988 at Island Road School, Aberdeen. The failure occurred during LPM works and involved some 800 m^3 of material and caused significant damage to the school. The geology comprised fine ash vitric tuff and eutaxite of the Ap Lei Chau Formation of the Repulse Bay Volcanic Group, on the limb of an anticline steeply dipping to the northeast and having a northwest trend. The area was reported as having a history of landsliding, dating back to at least 1945, and was used as a borrow area in 1924, and possibly as late as 1949.

The rock mass was deeply weathered, with completely decomposed tuff reaching 15 m thickness at mid-slope. This trough of deep weathering trended north west-south east and was considered to be "the result of hydrothermal alteration where later weathering effects penetrate deeper". Numerous kaolin veins considered to be of hydrothermal origin were present in the weathered tuff, with the most dominant set striking north-west.

The majority of the discontinuities in the weathered rock were generally close to very closely spaced and contained up to 30 mm of kaolin. These were "considered to have been formed by hydrothermal alteration, possibly resulting from hot aqueous solutions migrating along lines of weakness in the volcanic rocks during the late stages of a cooling granitic magma source at depth". However, as at the Tin Wan Hill site (3.10 (b) above), the association of kaolin with completely decomposed rock could suggest a weathering, rather than a hydrothermal origin for the kaolin. Joint measurements of kaolin infilled and non-kaolin infilled joints at the site, and joints in rock outcrops outside the site were recorded. The two dominant kaolin-free and kaolin-filled joint sets were of a similar orientation.

(e) Sui Sai Wan

Significant movement in April 1992, affecting a plan area of some 1000 m^2, occurred in a cut slope at Sui Sai Wan (also called Siu Sai Wan)(Ho & Evans, 1993). It was noted that the rock beneath the failed area was deeply weathered and was associated with "numerous clay-rich seams and clay-filled relict discontinuities". A single sample of the clay infill was tested and found to comprise kaolin and quartz. The kaolin comprised 87% halloysite and 13% kaolinite. Drained shear box tests were carried out with a lower bound value of $c' = 0$ kPa and $\phi' = 34°$. Ho and Evans (op. cit.) noted that kaolin infills may not have been fully saturated before shearing and that there were problems in aligning the shear box. Consequently it was considered that “the tests are over-estimates of the strength of infilled relict joints”.

4. GEOLOGICAL MODEL FOR KAOLIN-RICH ZONES WITH A WEATHERING ORIGIN

Whilst kaolin mineralogy differs between sites, suggesting different environmental conditions during formation, most sites show clear evidence of shearing and brecciation and multiple generations of kaolin. The infills appear to be commonly controlled by pre-existing discontinuities, typically associated with stress relief jointing, which may have been enlarged during weathering, providing physical space for deposition. Also, kaolin often infills relict tectonic joints, albeit to a lesser extent generally than stress relief joints. A few samples display irregular infill/saprolite contacts, suggesting progressive deposition of the kaolin away from the discontinuity (Plate 21).

These findings support the idea of kaolin migrating during weathering, principally in solution, but also to some extent physically also. This movement can result in both a broad dissemination of kaolin throughout the weathered material and its preferential deposition in relict discontinuities (Figure 9). As weathering progresses into the rock mass, volumetric changes will generate differential stresses. One way in which the stresses can be dissipated is by movement along the kaolin-infilled relict discontinuities. This could explain the presence of some slickensides observed in the field and structural fabrics observed on a micro-scale, and might result in dilation of the discontinuities allowing yet further kaolin accumulation to occur.

Based on the evidence of field exposures and mineralogical testing, most kaolin-rich zones in Hong Kong are considered to be of a weathering origin. A few exceptions are probably formed by hydrothermal alteration, but insufficient data are available on which to base a model of their occurrences. The importance of producing a geological model for the occurrence of kaolin in Hong Kong is fundamental, when considering cut slope design (Morgenstern, 2000), in reducing its the potentially adverse effects. The following model (Parry et al., 2000a and b) is suggested for the formation of most kaolin-rich zones formed as a result of weathering of igneous (granite and volcanic) rocks in Hong Kong:

(a) Weathering penetrates the rock mass preferentially along pre-existing zones of weakness such as joints and shears (Figure 9). This promotes the genesis of kaolin minerals from the weathering mainly of feldspars and biotite, which are the dominant minerals in the widespread igneous rocks in Hong Kong.

(b) After genesis, kaolin either remains virtually in situ, often forming pseudomorphs after individual crystals, or migrates, mainly in solution but with some secondary physical reworking and redeposition. This movement may be very localized, resulting in a broad dissemination of kaolin throughout the weathered material. Alternatively the kaolin may migrate further and become preferentially deposited in relict discontinuities.

(c) As weathering progresses into the rock mass, volume changes generate differential stresses. These dissipate by movement on relict discontinuities, now partially infilled with kaolin. This results in the generation of slickensides and other structural fabrics within the kaolin infills, and dilation, allowing further kaolin accumulation to occur.

(d) The cyclic deposition of kaolin, often with changing composition and accompanying ground deformation, continues throughout weathering of the rock mass. The cycle may be interrupted, as pathways for groundwater movement are infilled by kaolin, which also acts as an aquiclude.

(e) Preferential sites of weathering, especially at and close to the weathering front, along faults and other major discontinuities, including some contacts between geological units, may also be preferential sites of kaolin development (Figure 9).

5. SUMMARY

Based on the findings of the work completed to date, the following key observations can be made on the origin, distribution and characteristics of kaolin-rich zones in weathered rocks in Hong Kong.

(a) Nature of kaolin-rich zones

Kaolin-rich zones commonly include infills that occupy discontinuities, including joints, faults, shear zones and lithological contacts, within volcanic and granitic rocks. Kaolin veins, though less common, also occur.

A geological model has been developed for kaolin-rich zones that have a weathering origin. This helps to explain the occurrence of most of the kaolin-rich zones in volcanic and granitic rocks and the role of weathering processes and groundwater movement in their genesis and distribution. However, there is also local evidence in Hong Kong that some kaolin-rich zones contain veins that are of hydrothermal origin.

Individual kaolin veins and infills and kaolin-rich zones generally vary in thickness from millimetres to tens of millimetres, but they may be up to hundreds of millimetres thick. They usually have limited lateral persistence but may extend up to 60 m, and possibly further.

Kaolin veins and infills contain mainly halloysite and kaolinite in varying proportions. The kaolin is often associated with manganese oxide deposits.

Kaolin-rich zones have commonly undergone previous episodes of shearing, especially when associated with day-lighting discontinuities. Evidence of previous movement associated with kaolin-rich zones is relatively common and typically includes slickensides within, and brecciation and shear deformation of, the kaolin.

(b) Distribution of kaolin-rich zones

Kaolin in general and kaolin-rich zones in particular, are relatively uncommon in Grade I to III rock, except at and close to the weathering front (the boundary below which rock predominates in a partially weathered rock mass profile). They are both more common in saprolite. This is especially the case where the transition from Grades II and III rock (respectively slightly and moderately decomposed rock) to Grade IV rock (highly decomposed) and more particularly Grade V rock (completely decomposed), is a planar interface. Such occurrences are often shallowly dipping and sub-parallel to the overlying topography.

Kaolin-rich zones may also occur within, and above local depressions in the weathering front caused by zones of faulting, discontinuities with close spacing, and subvertical eutaxitic foliation.

Occasionally, kaolin infills, and rarely kaolin-rich zones, occur within ancient colluvial deposits of Pleistocene age. They typically do so within the matrix of the deposits and around some clasts.

(c) Identification of kaolin-rich zones

Where kaolin-rich zones are known, or suspected, at a site, consideration of the genesis of the kaolin may help the investigation of the location and spatial extent of the kaolin-rich zones. In particular, the geological model established for kaolin-rich zones that have a weathering origin indicates that they tend to concentrate at/close to the weathering front and within pre-existing discontinuities.

Determining the orientation, lateral persistence and strength of individual kaolin infills normally entails detailed ground investigation and engineering geological mapping. Particular emphasis should be placed on physical inspection of material wherever possible. In a cut slope, for example, this can be achieved through full-face mapping and logging, after stripping surface cover, mapping of adjacent exposures, excavation and logging of trial pits and trenches, and logging of drillholes. The geological model should be verified during construction.

Where drillholes are undertaken, continuous sampling may also be undertaken to determine the thickness and extent of individual kaolin infills. Where continuously sampled drillholes are not viable, gamma density and spectral gamma ray downhole logging have the potential to locate kaolin-rich zones.

Other features that may indicate the presence of kaolin-rich zones, especially in cut slopes, include stratification dipping out of the slope (e.g. indicated by eutaxitic foliation in some fine ash tuffs), zones of continuous seepage, and clusters of previous slope failures with indications of control by geological structures.

Guidelines for identifying kaolin-rich zones have been promulgated by the Geotechnical Engineering Office, Civil Engineering Department, in Technical Guidance Note (TGN) No. 4 (GEO, 2001), and, recommended downhole geophysical techniques are described in TGN No. 3 (GEO, 2000b). Related guidance regarding ground investigation is also contained within TGN No. 2 (GEO, 2000a).

(d) Shear strength of kaolin-rich zones

Obtaining representative shear strength data of kaolin-rich zones from conventional laboratory testing is not easy. Due care should be given to obtaining suitable samples, aligning pre-existing soil structures and slickensided surfaces with the direction of shearing, overcoming effects of volume change during testing, etc. Past experience indicates that laboratory shear strength test results often show significant scatter and their interpretation requires considerable care.

The shear strength of kaolin-rich material found in Hong Kong is controlled by the composition of the two main kaolin minerals, kaolinite and halloysite. The higher the proportion of kaolinite, the lower would be the peak and residual strength. Hence, it is advisable that, where the shear strength of a kaolin-rich zone is of concern, mineralogical tests should be carried out in addition to shear strength tests to establish the mineralogical composition of the material. This will provide useful information to facilitate interpretation of the shear strength test results and determination of the appropriate design parameters. Similarly, such arrangements are also useful where back-analysis is used to assess the shear strength parameters of kaolin-rich zones.

In future, when more data are collated, there is the possibility of establishing an empirical correlation between shear strength parameters and the mineralogical composition of kaolin-rich zones in Hong Kong.

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Table 1 - Peak Shear Strength Values for Saprolite and Kaolin

Site	Saprolite[#]		Kaolin[##]	
	c'(kPa)	ϕ'(°)	c'(kPa)	ϕ'(°)
Fei Tsui Road*	0	35	0	29
Fei Tsui Road**	-	-	0	22
Sum Wan Road*	5	38	0	21
Sai Sha Road*	6.5	33	0	19
Sai Sha Road**	-	-	0	10
Shek Kip Mei*	8	38	0	20
Shek Kip Mei**	-	-	0	16

Notes: (1) # undrained triaxial test.
(2) ## direct shear test.
(3) * best fit.
(4) ** lower bound.

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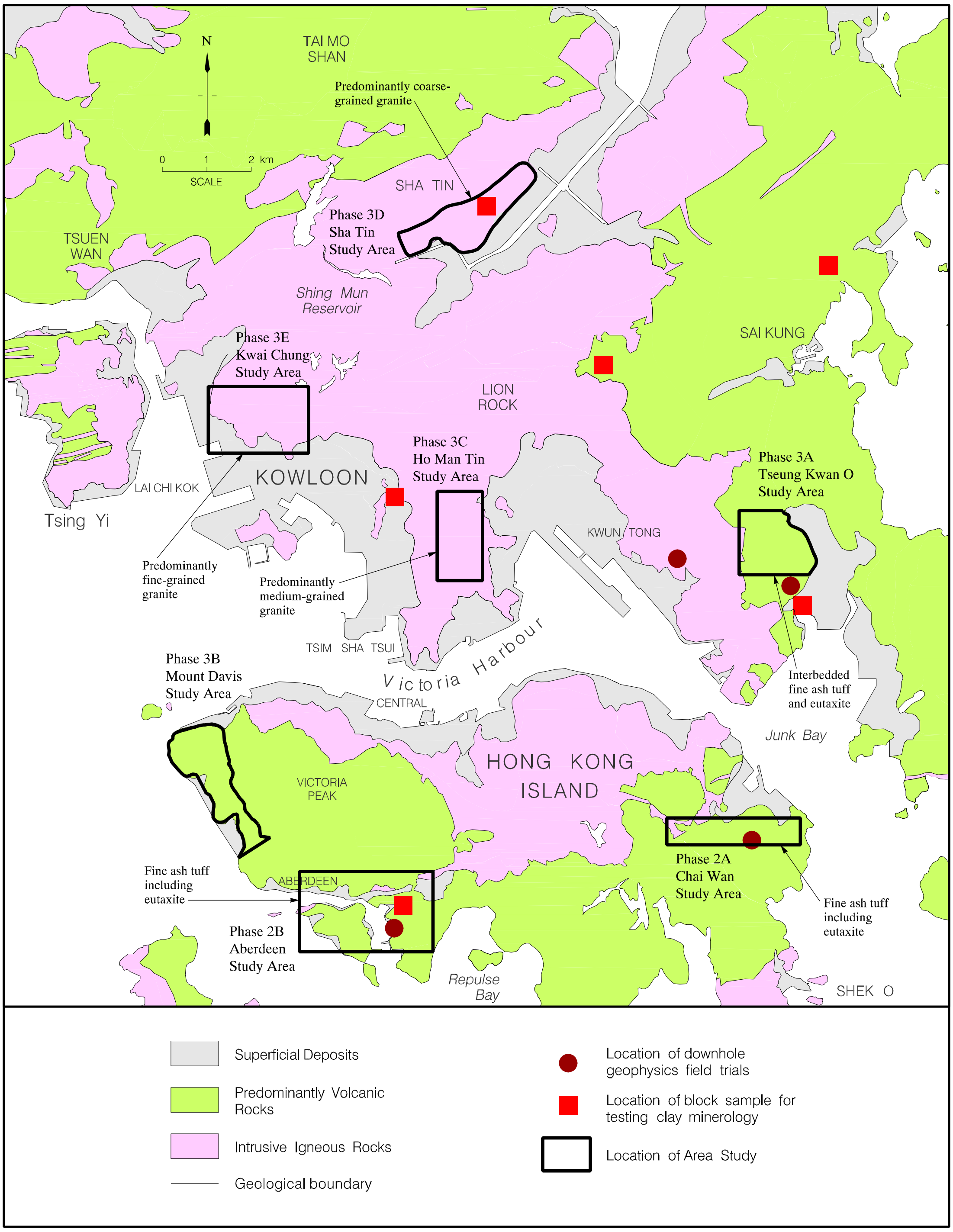
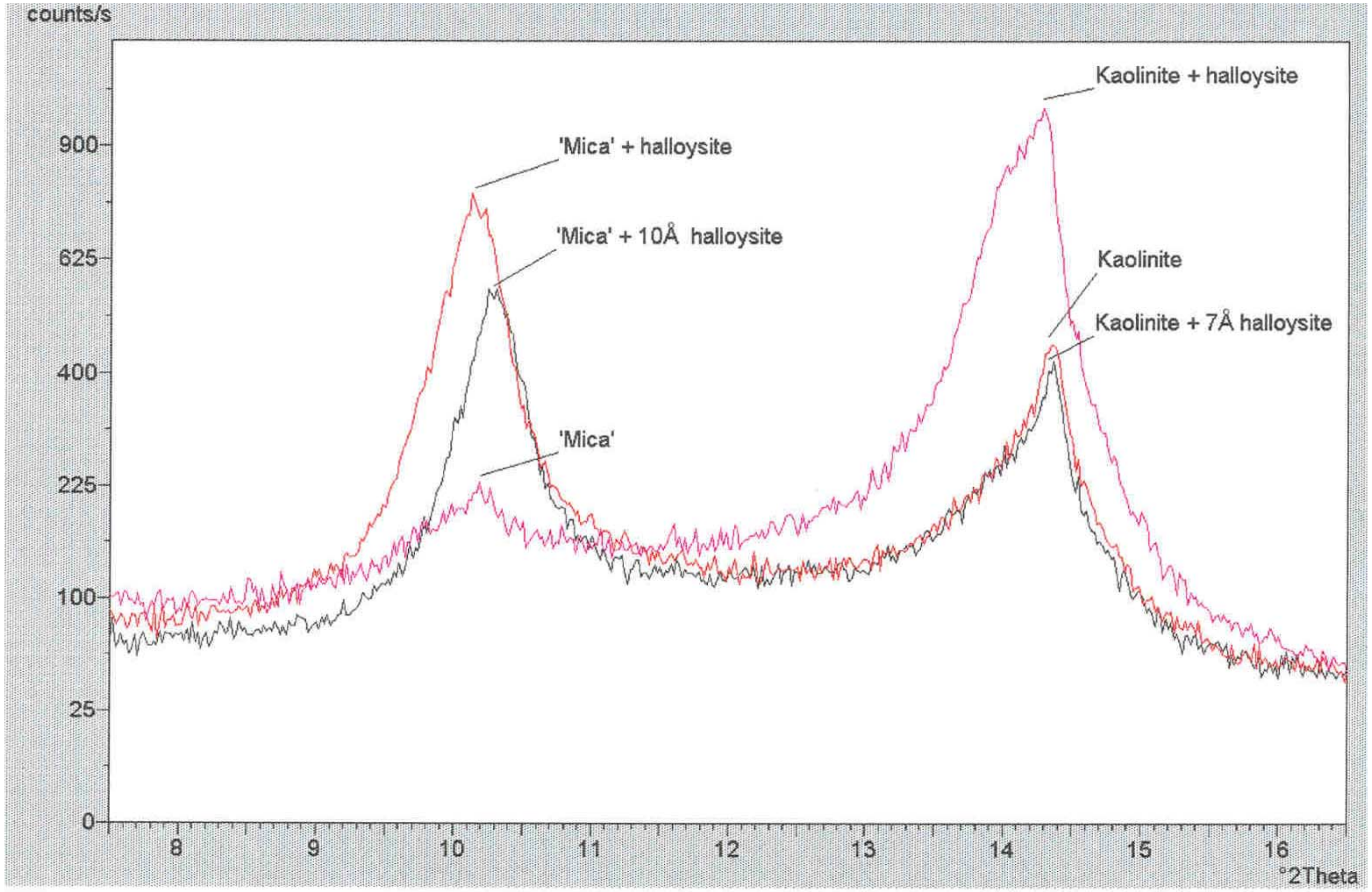
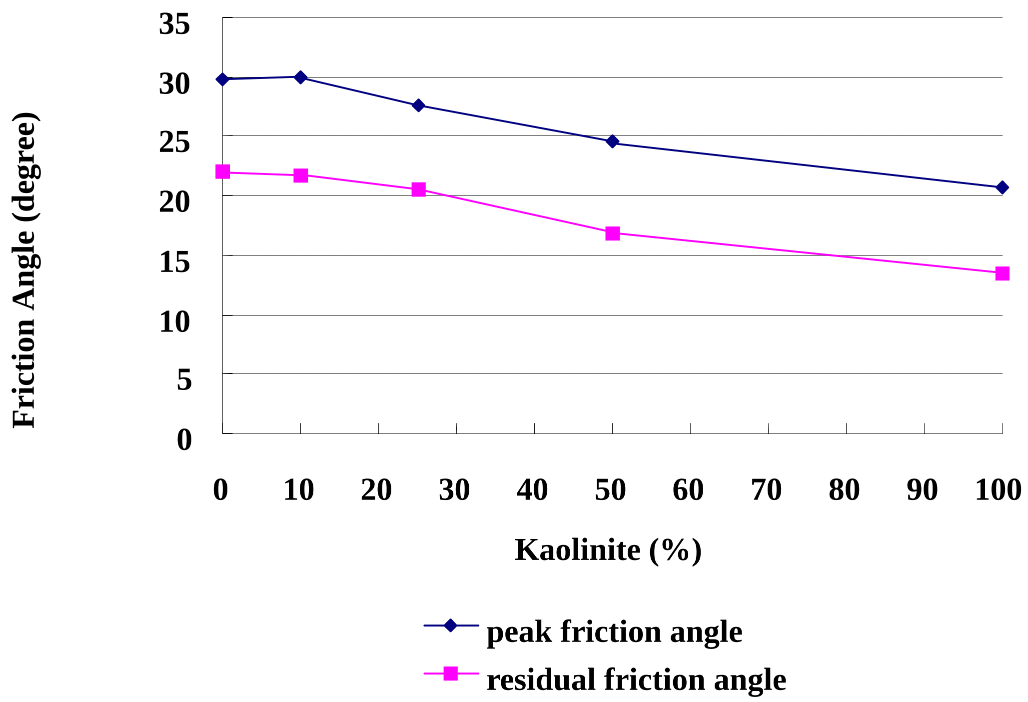


Figure 1 - Locations of Area Studies, Downhole Geophysics Trial Sites, and Block Samples for Mineralogy Testing



(black trace = wet run; red trace = formamide intercalation; magenta trace = heated to 110°C/90 minutes)

Figure 2 - XRD Traces Illustrating the Effects of Heating and Formamide Intercalation



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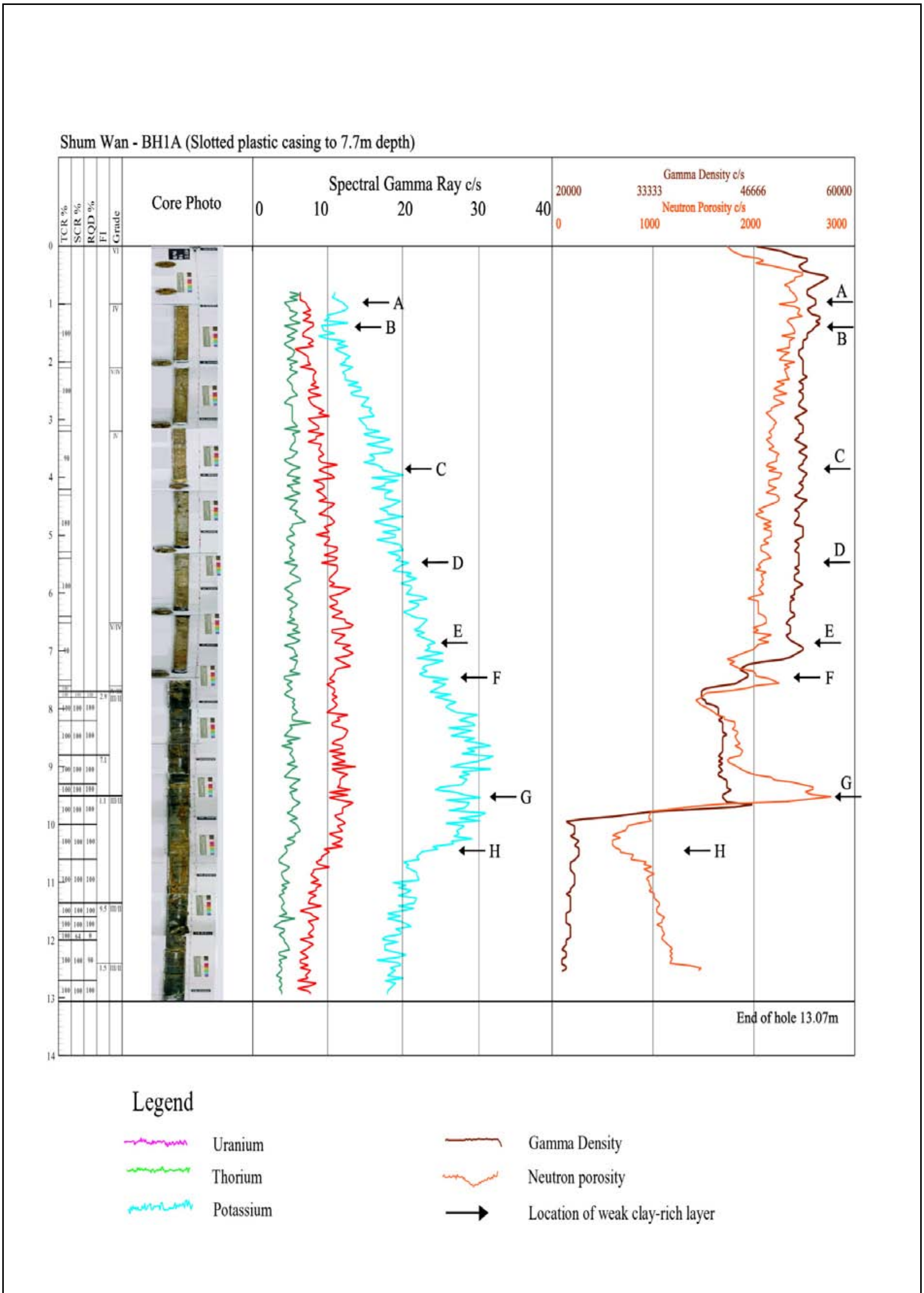

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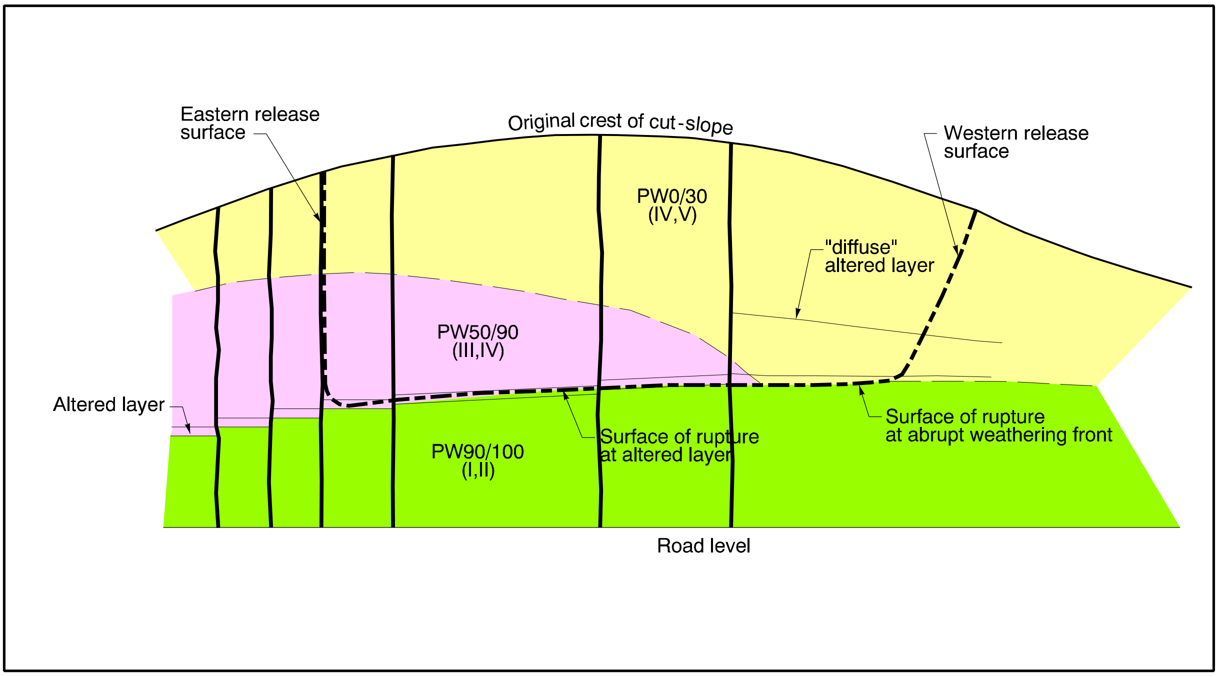

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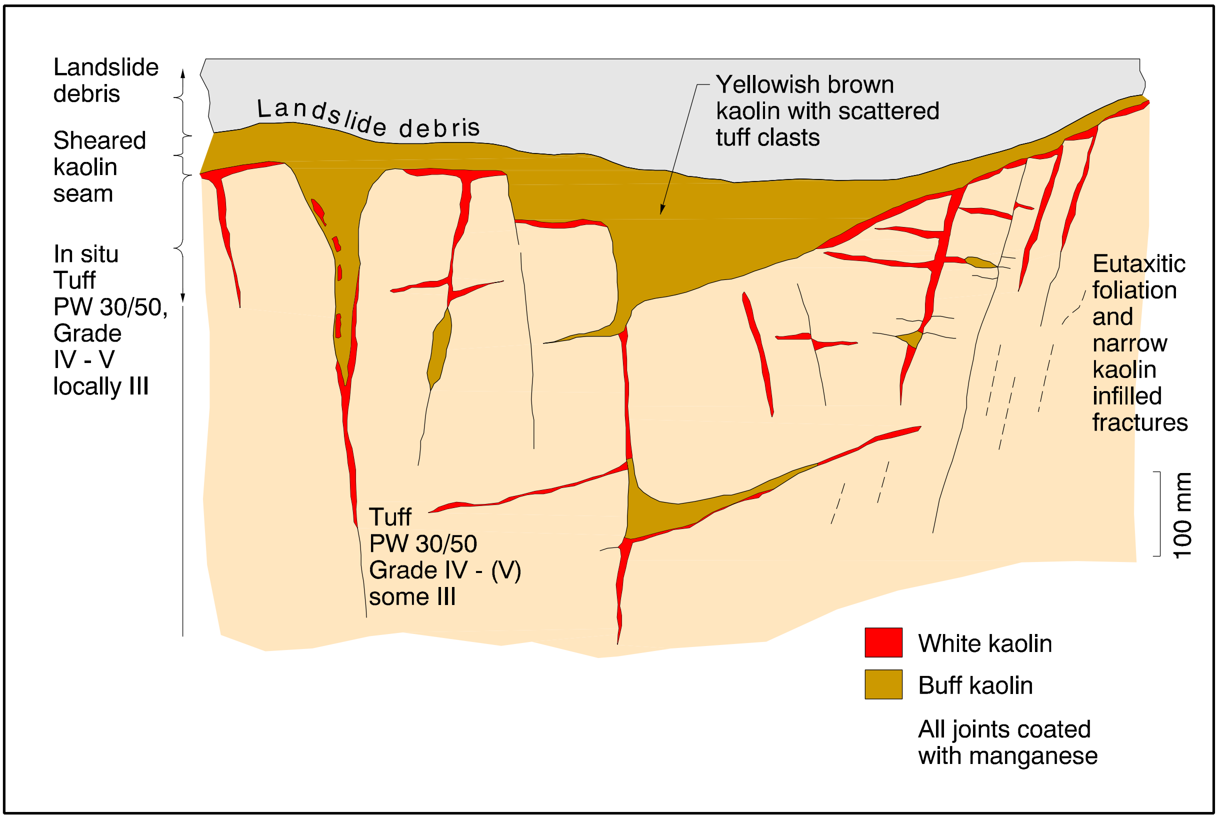

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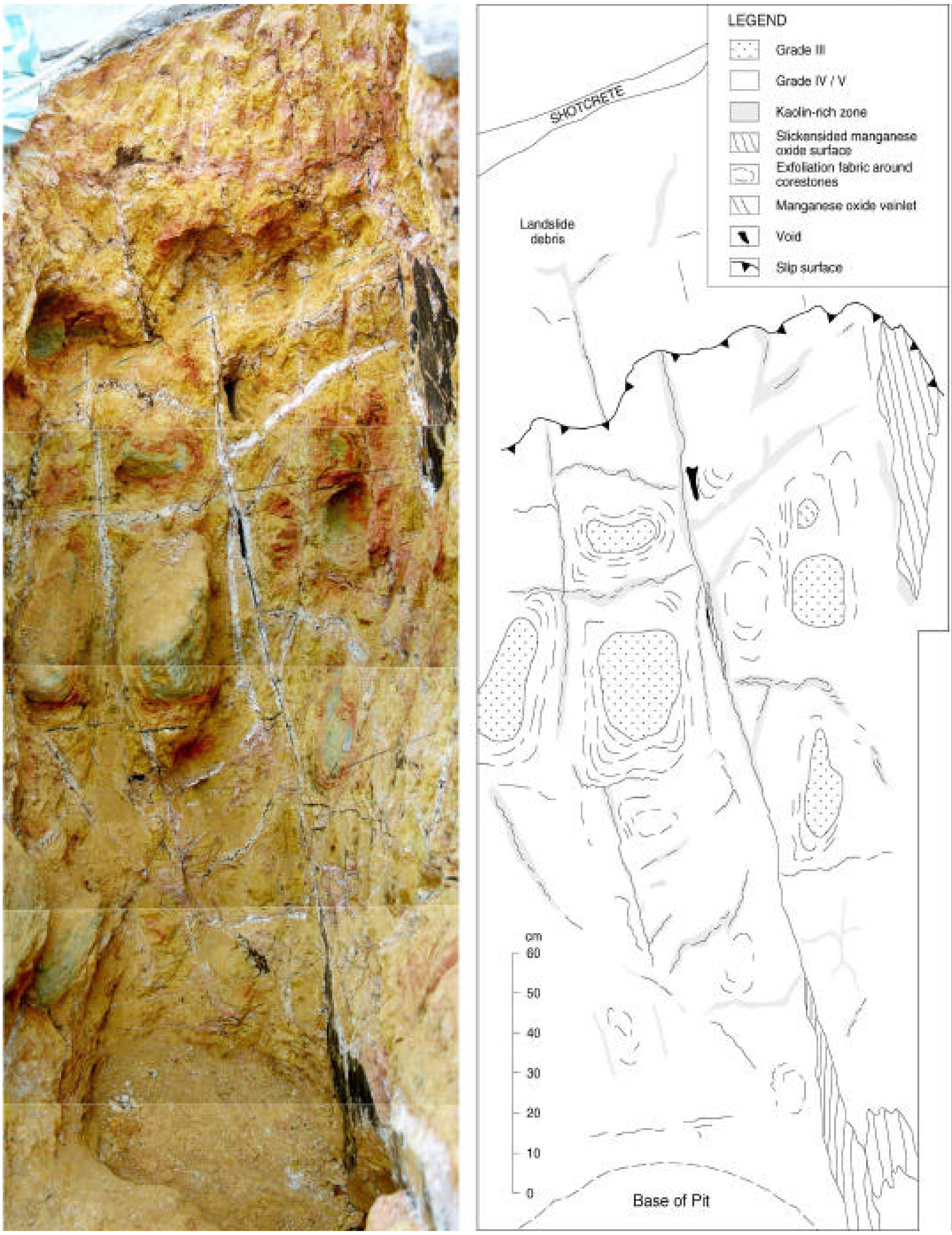

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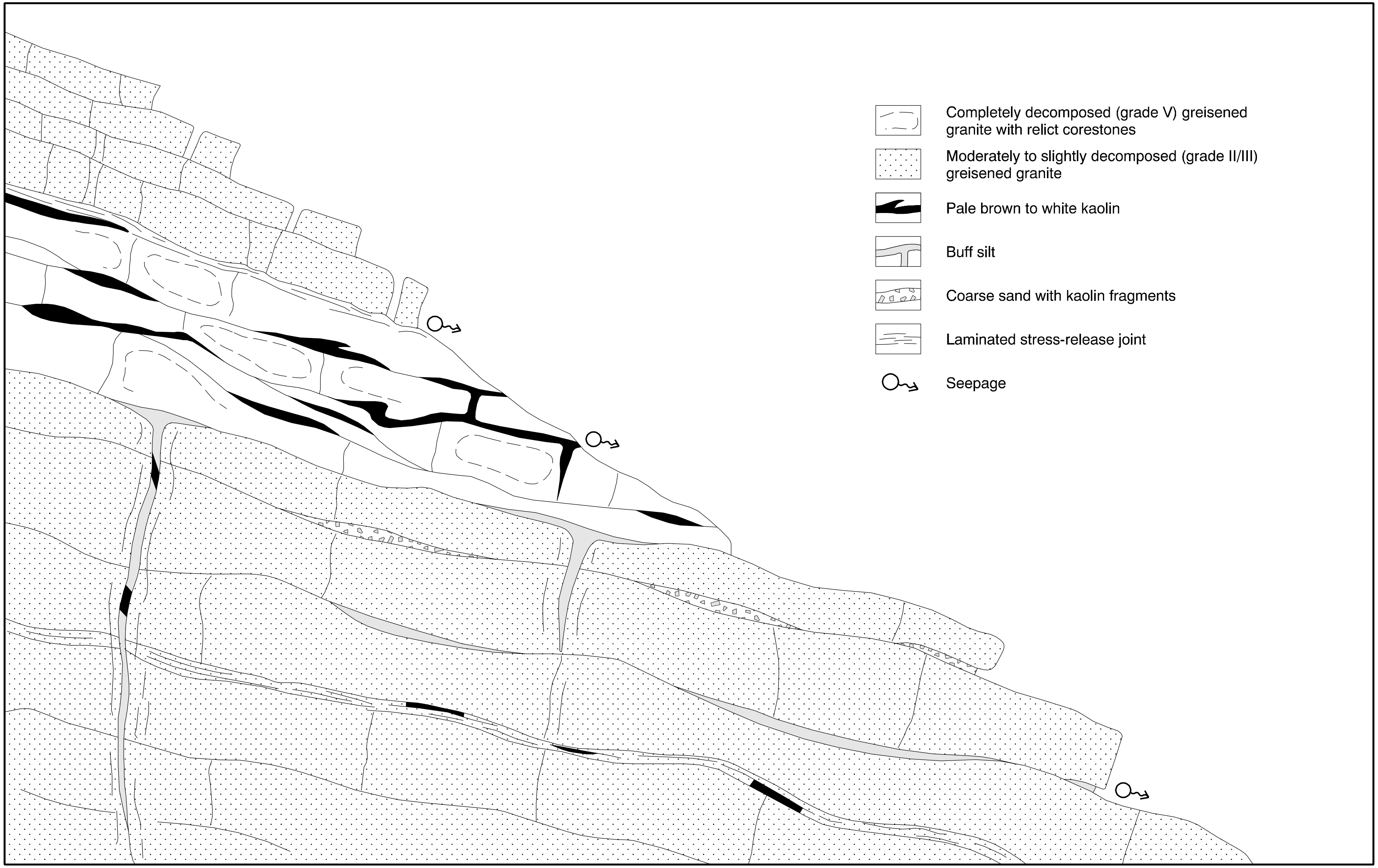

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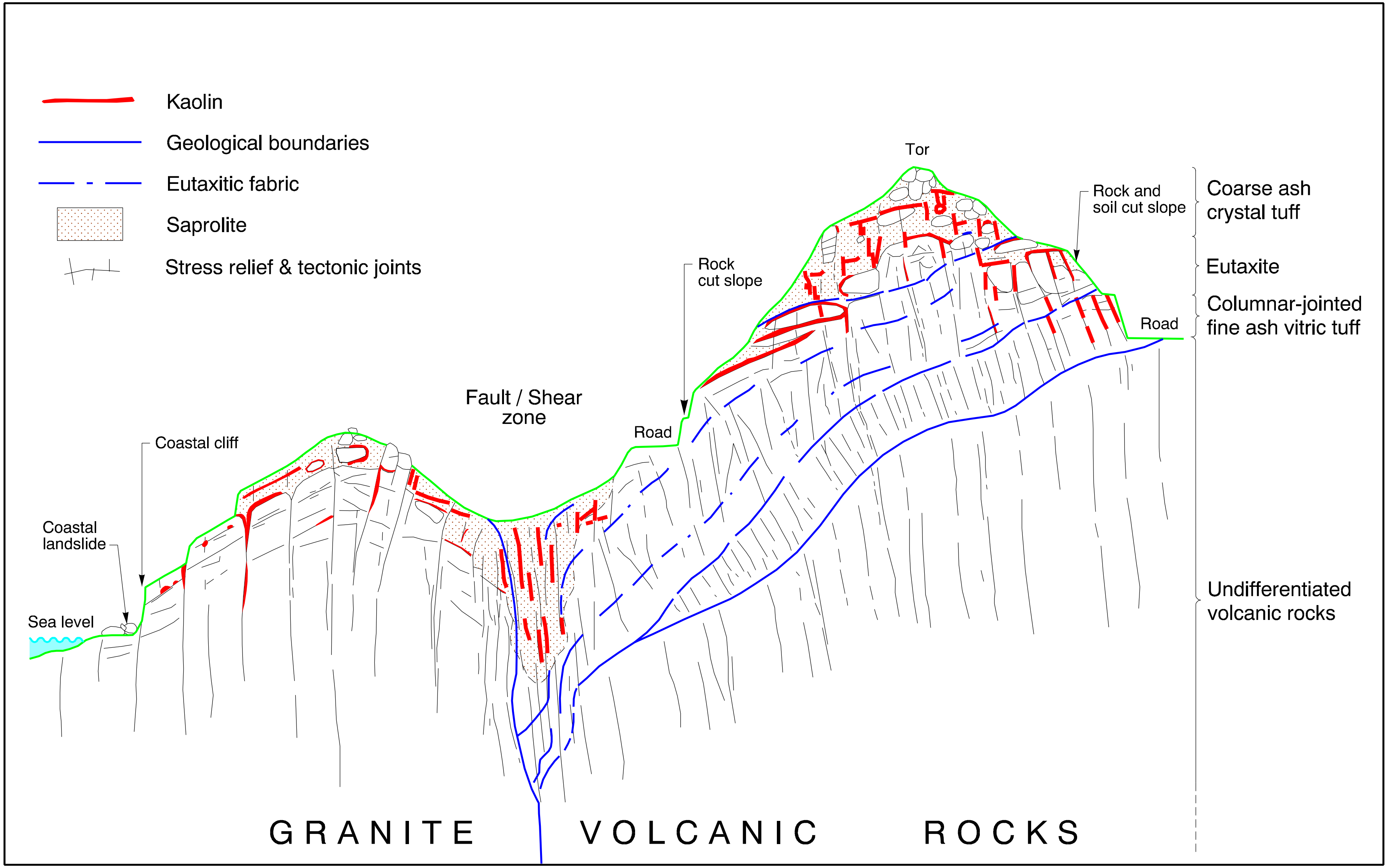

Figure 9 - Schematic Representation of Kaolin of a Weathering Origin in Both Weathered Granite and Volcanic Rocks

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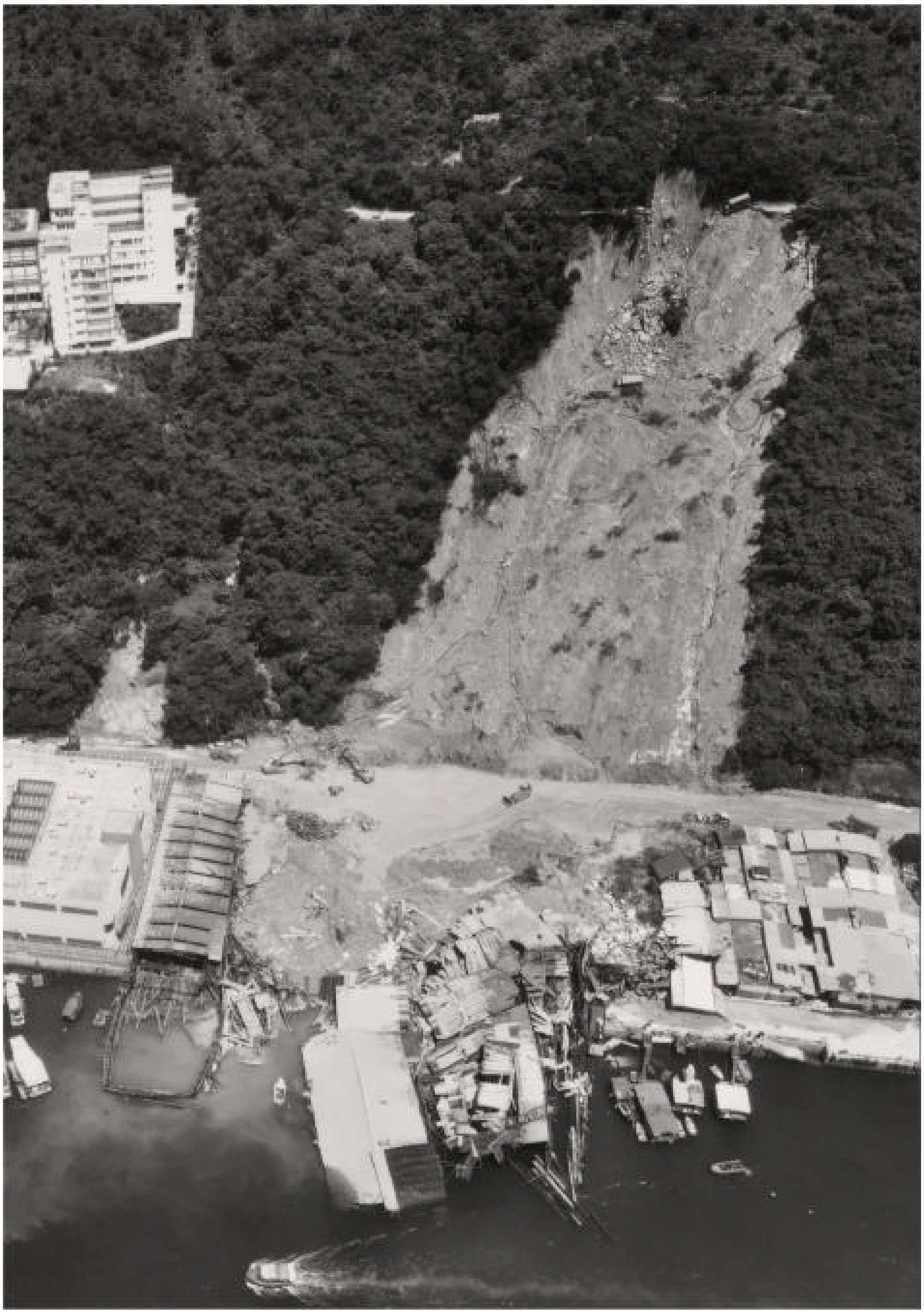
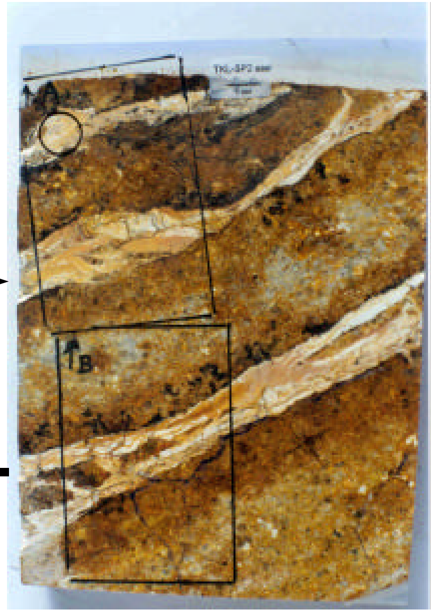


Plate 2 - Shum Wan Road Landslide, August 13, 1995

Plate 3(a) - Eastern Face of Block Sample SP2, from Tiu Keng Leng. Completely Decomposed Coarse-grained Greissenised Granite. Note Southerly Dipping (~20°) Very Soft Pink (7.5 yr 7/3) Mottled White Clay Infills. Red Outlines Location of Sub-sample for Mineralogy Testing



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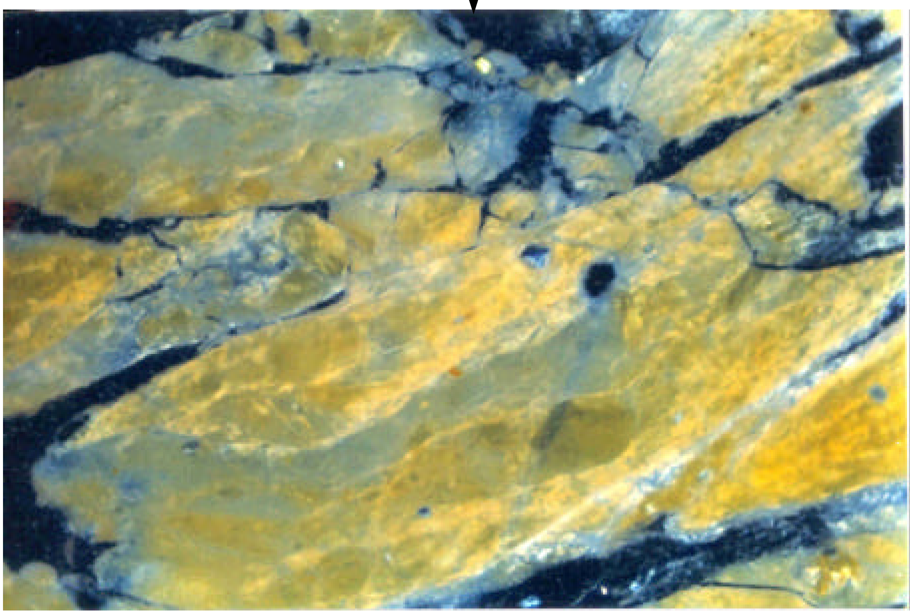

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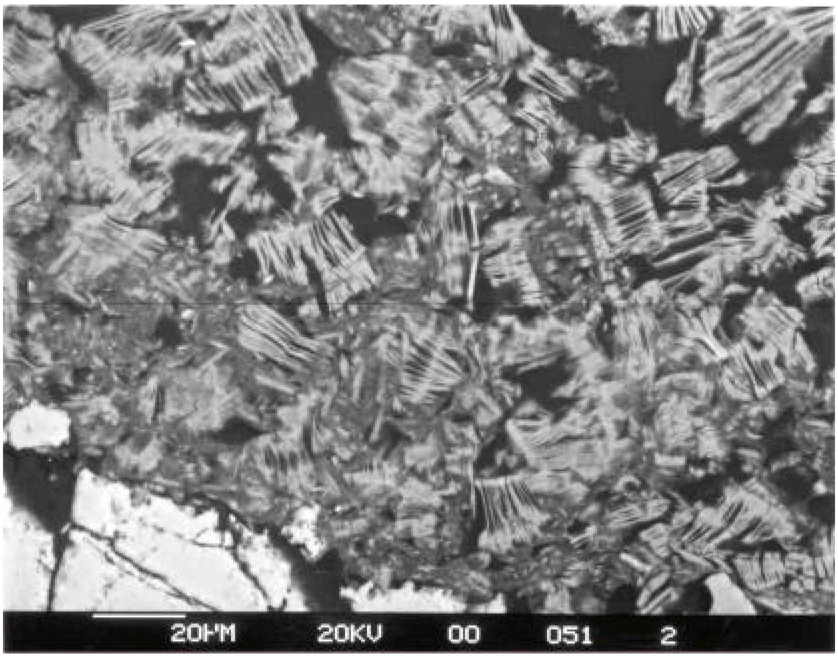

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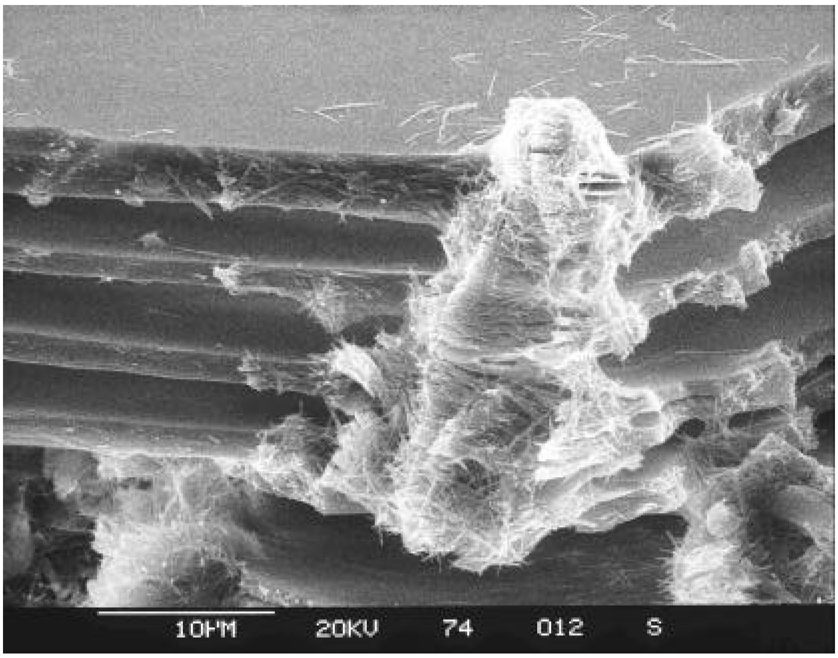

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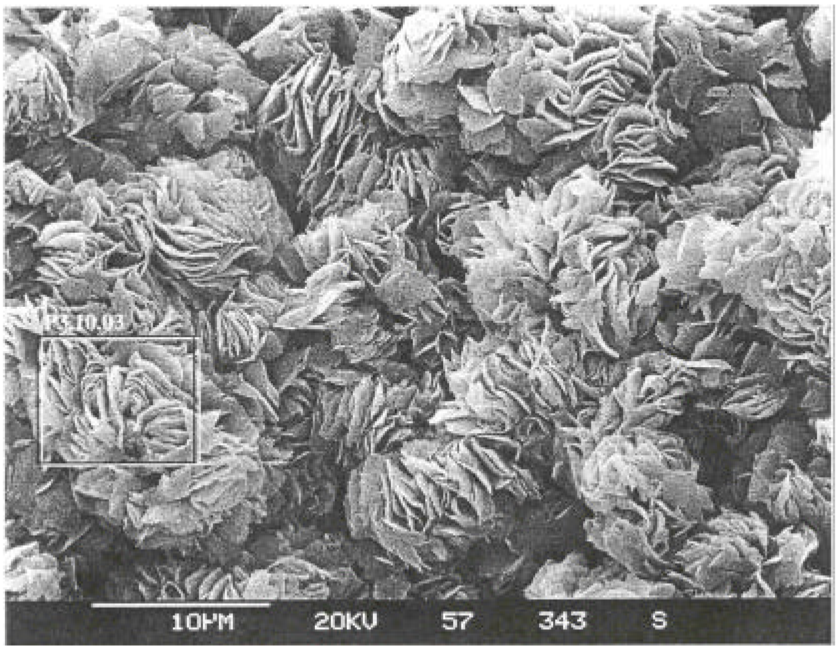

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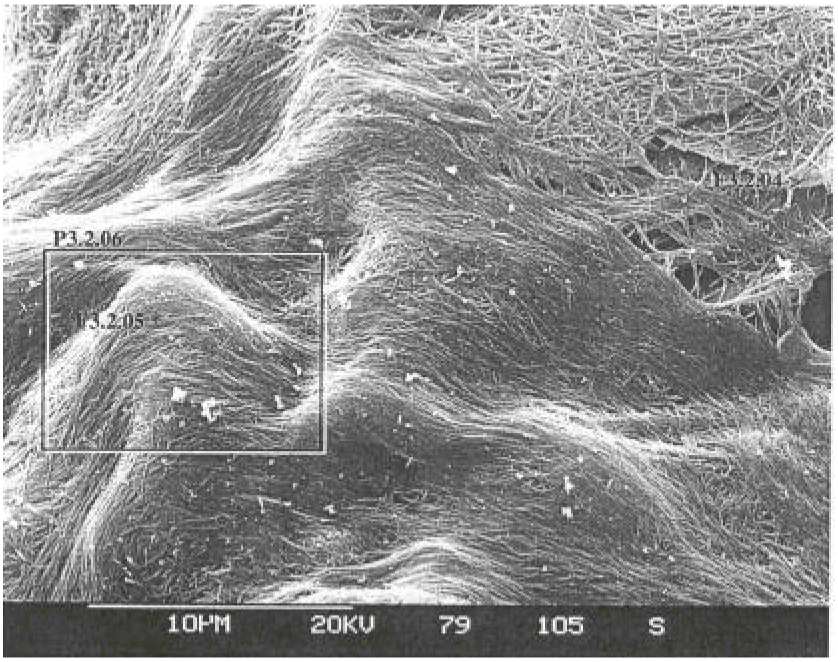

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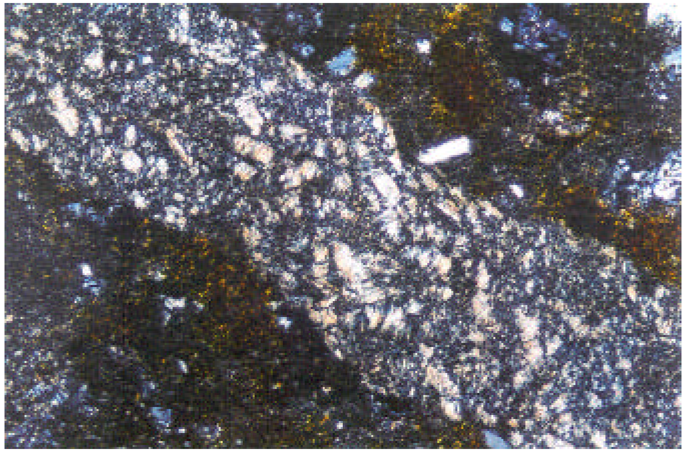

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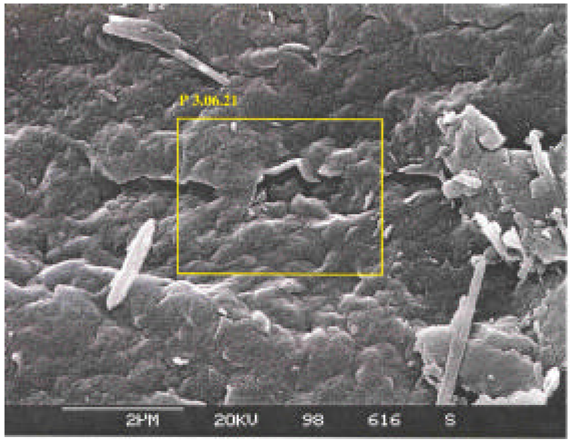

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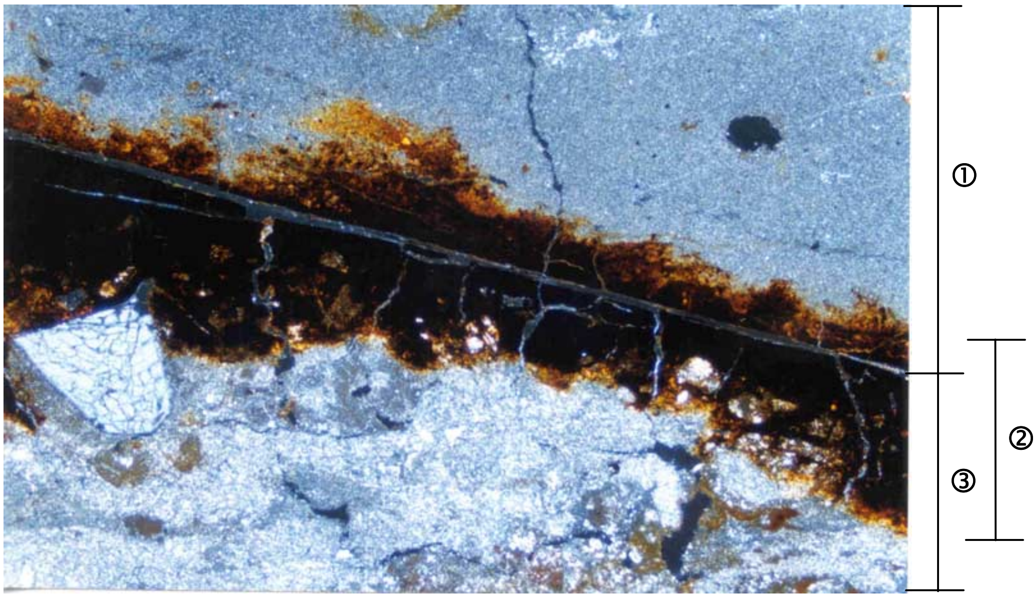


Plate 7 (a) - Optical Micrograph of Thin Section from SSR-D1, Sai Sha Road. Intense Manganese Oxide Staining ② of Ultrafine Kaolin ① and Kaolinised Tuff ③ along Shear Plane. Width of View 6.35 mm (after CSIRO, 2000)

Plate 7 (b) - Optical Micrograph of Thin Section from S2, Shek Kip Mei, Manganese Oxide Stained Foliated Kaolin ② at Base of White Kaolin Infill ① overlying Brecciated Granite ③. Width of View 6.35 mm (after CSIRO, 2000)

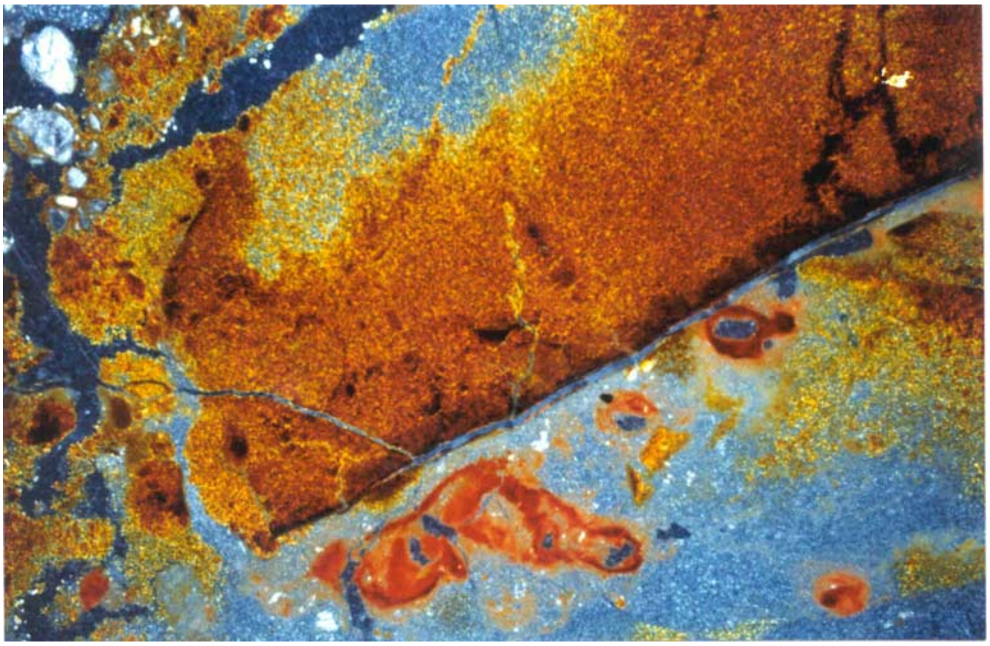


Plate 8 (a) - Optical Micrograph of Thin Section from SSR-1, Sai Sha Road. Brecciated Stained Kaolin Incorporated in Later Clear Kaolin. Width of View 2.7 mm (after CSIRO, 1999)

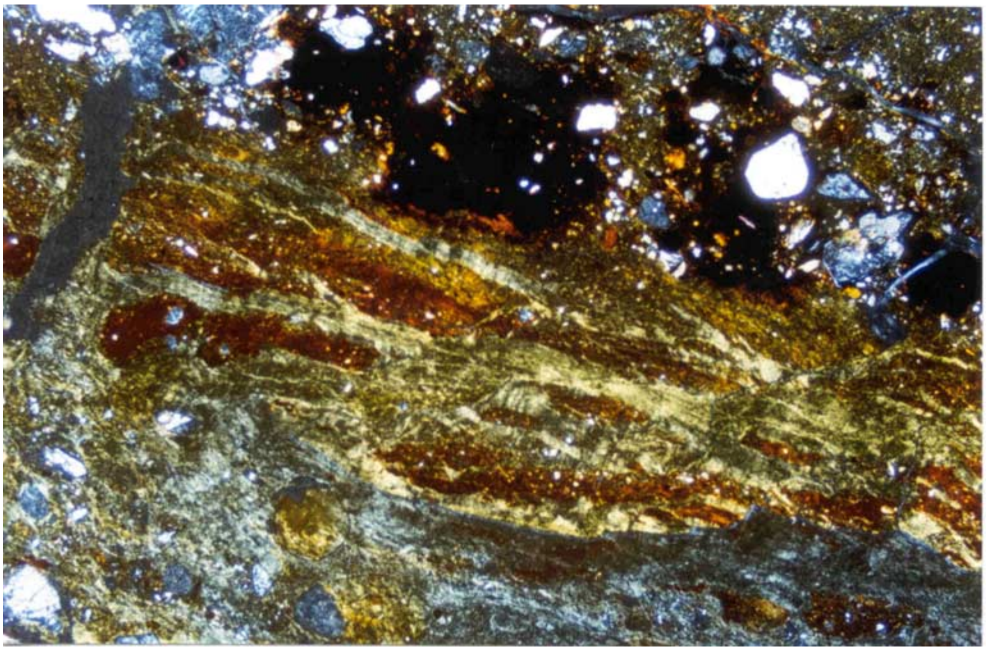


Plate 8 (b) - Optical Micrograph of Thin Section from TKL-1, Tiu Keng Leng. Weakly Foliated, Stained Kaolin with Entrained Quartz. Width of View 6.35 mm (after CSRIO, 1999)

Plate 8 (c) - Optical Micrograph of Thin Section from S12, Shum Wan Road. Complex Shear Foliation and Brecciation. Width of View 6.35 mm (after CSIRO, 2000)

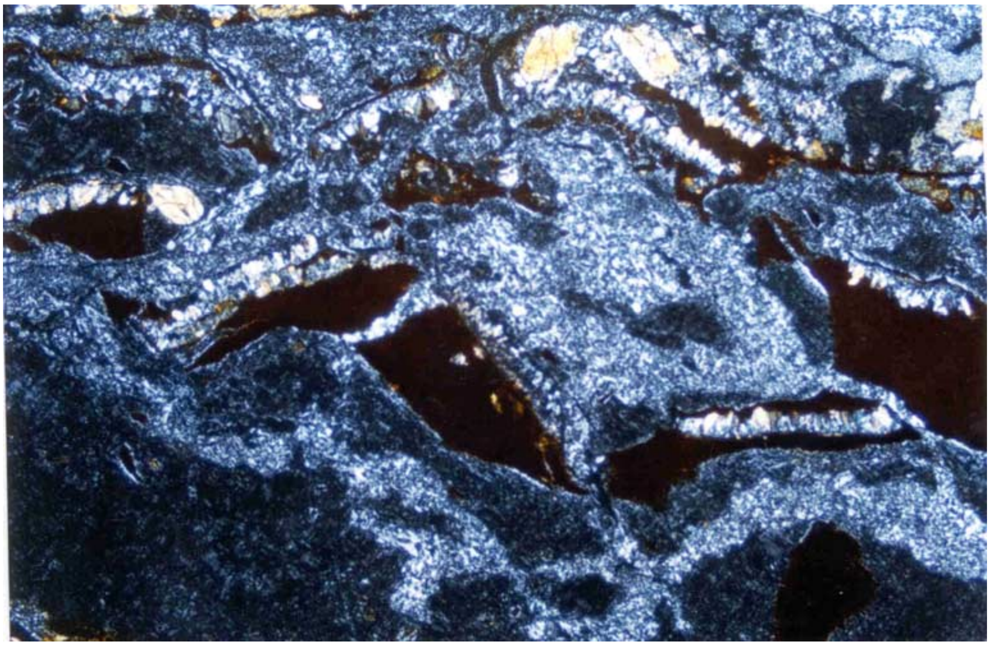


Plate 8 (d) - Optical Micrograph of Thin Section from TK2, Tiu Keng Leng. Wall Rock Sheared and Incorporated in Later Kaolin Infill. Width of View 6.35 mm (after CSIRO, 1999)

Plate 8 (e) - Optical Micrograph of Thin Section from S1, Fei Ngo Shan. Shear Deformation through Kaolin Infill. Width of View 6.35 mm (after CSRIO, 1999)

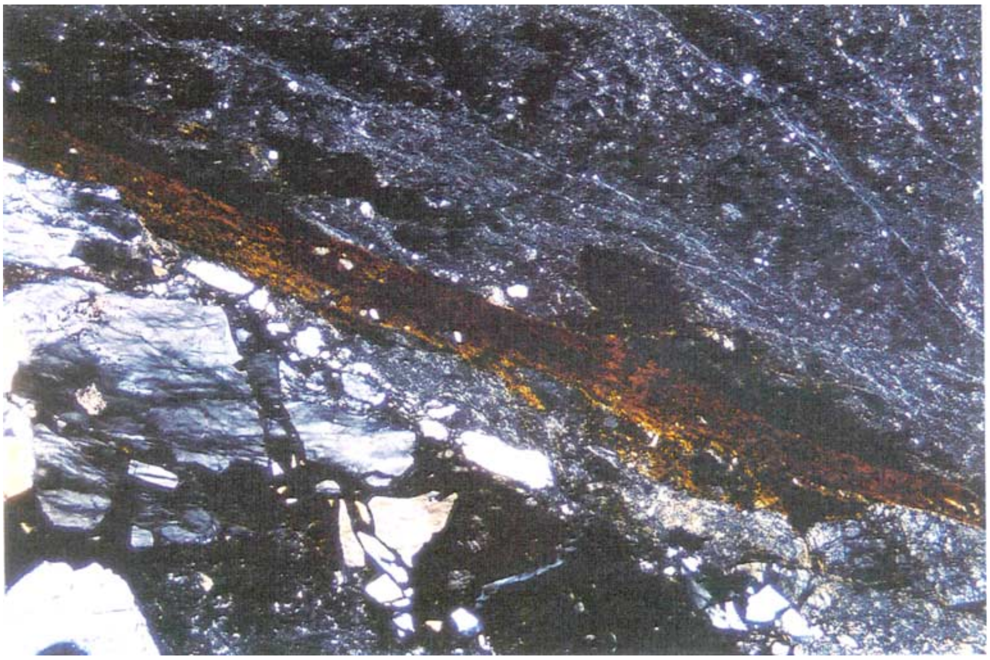


Plate 8 (f) - Optical Micrograph of Thin Section from S2, Shek Kip Mei Manganese Oxide Stained Shear Plane at Base of Foliated Kaolin. Width of View 6.35 mm (after CSIRO, 2000)

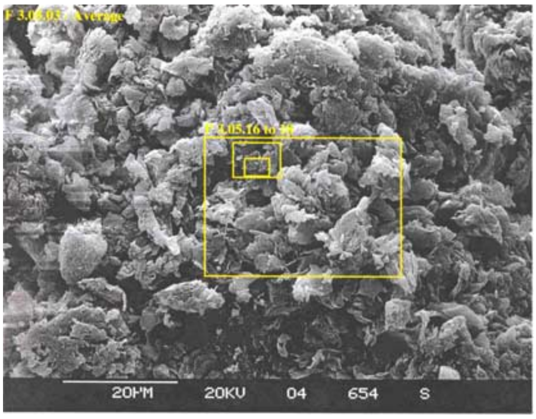


Plate 9 (a) - Secondary SEM of Block Sample S1, Fei Ngo Shan.
Unorientated Kaolin Plates at Center of Clay Infill

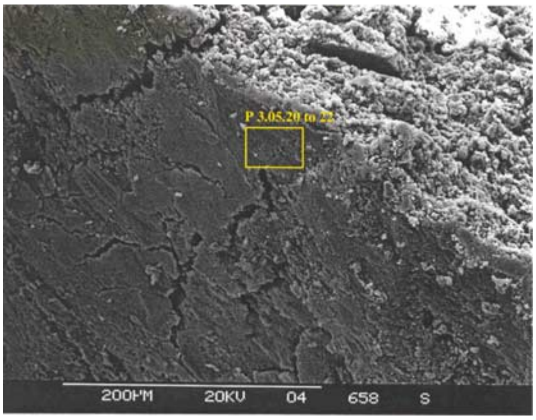


Plate 9 (b) - Secondary SEM of Block Sample S1, Fei Ngo Shan.
Slickensided Surface of Kaolin (Plate 9 (c) Shows Enlargement of Outlined Area)

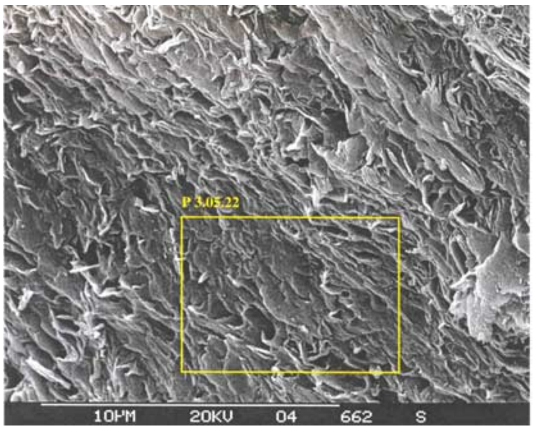


Plate 9 (c) - Secondary SEM of Block Sample S1, Fei Ngo Shan. Orientated Kaolinite Plates on Slickensided Surface

Plate 10 - Views Southwest towards Cut Slope at Fei Tsui Road in 1977 (above) and in 1995 after Failure (below). The Dark Band in Mid-slope in 1977 Is the Kaolin-rich Layer that Influenced Failure in 1995; in 1997, Chunam Covered Soil, but Rock (Fine Ash Tuff of the Che Kwu Shan Formation) Was Unprotected (after Kirk et al., 1997)

Plate 11 - Block Sample from the Shum Wan Road Landslide (1995), Showing Two Types of Kaolin Infill (Buff and White) of Relict Joints and Displacement of Some Previously Kaolin-infilled Joints

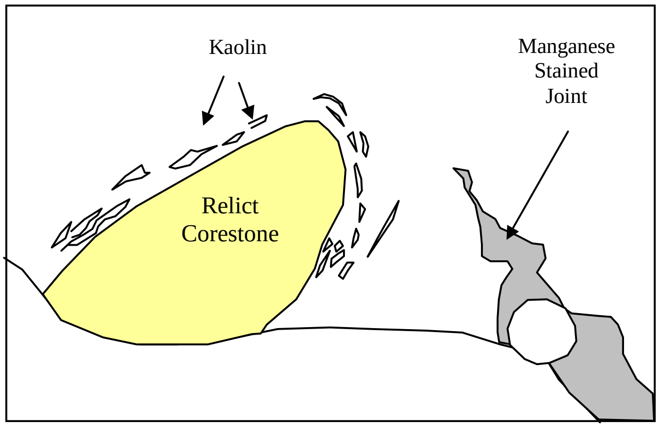


Plate 12 - Concentric Distribution of Kaolin Infills around Relict Corestone, Sai Sha Road Landslide Site (1998)

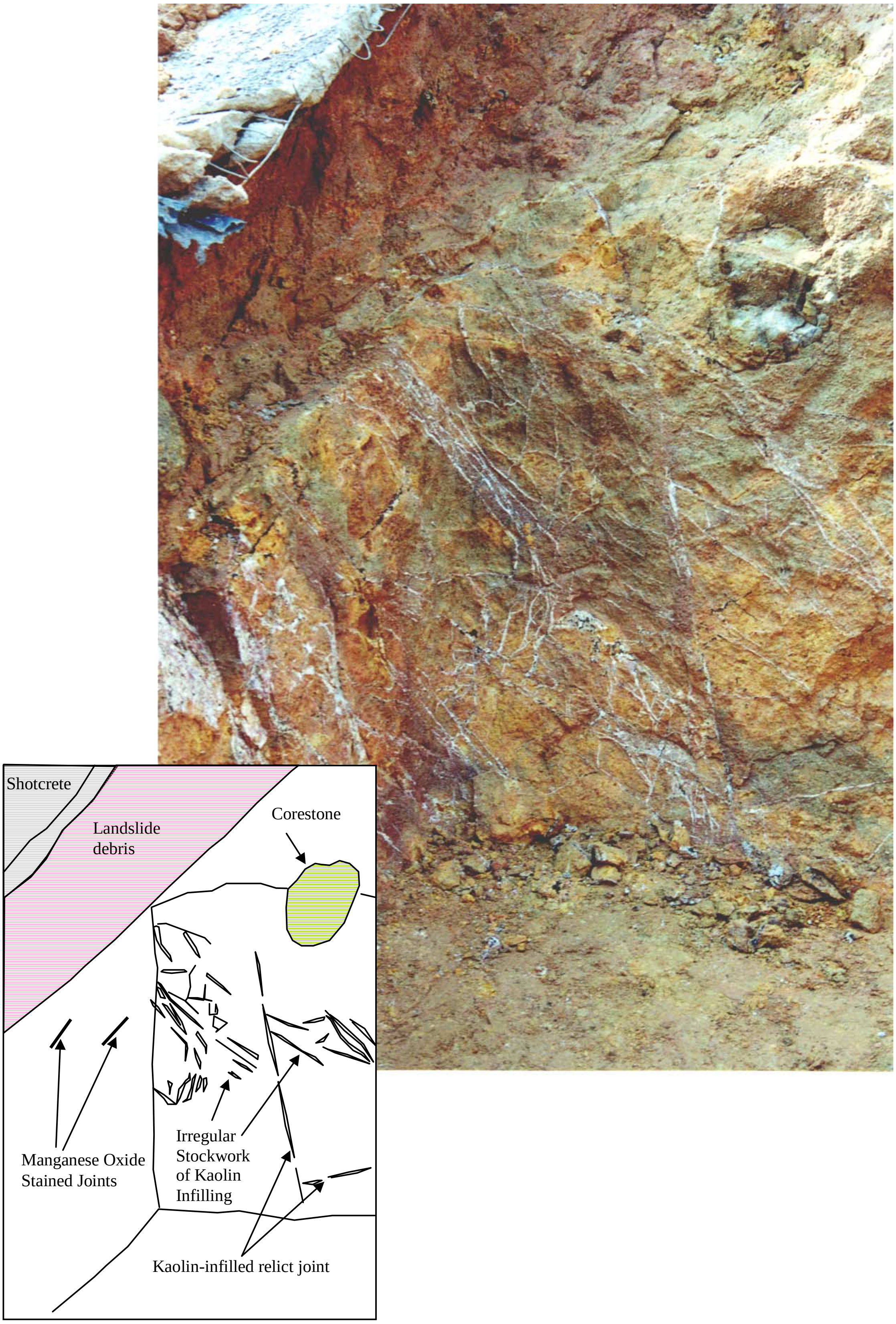


Plate 13 - Irregular Distribution of Kaolin Veins beneath Surface of Rupture in Trial Trench 1 at Fei Ngo Shan Landslide Site (1998)

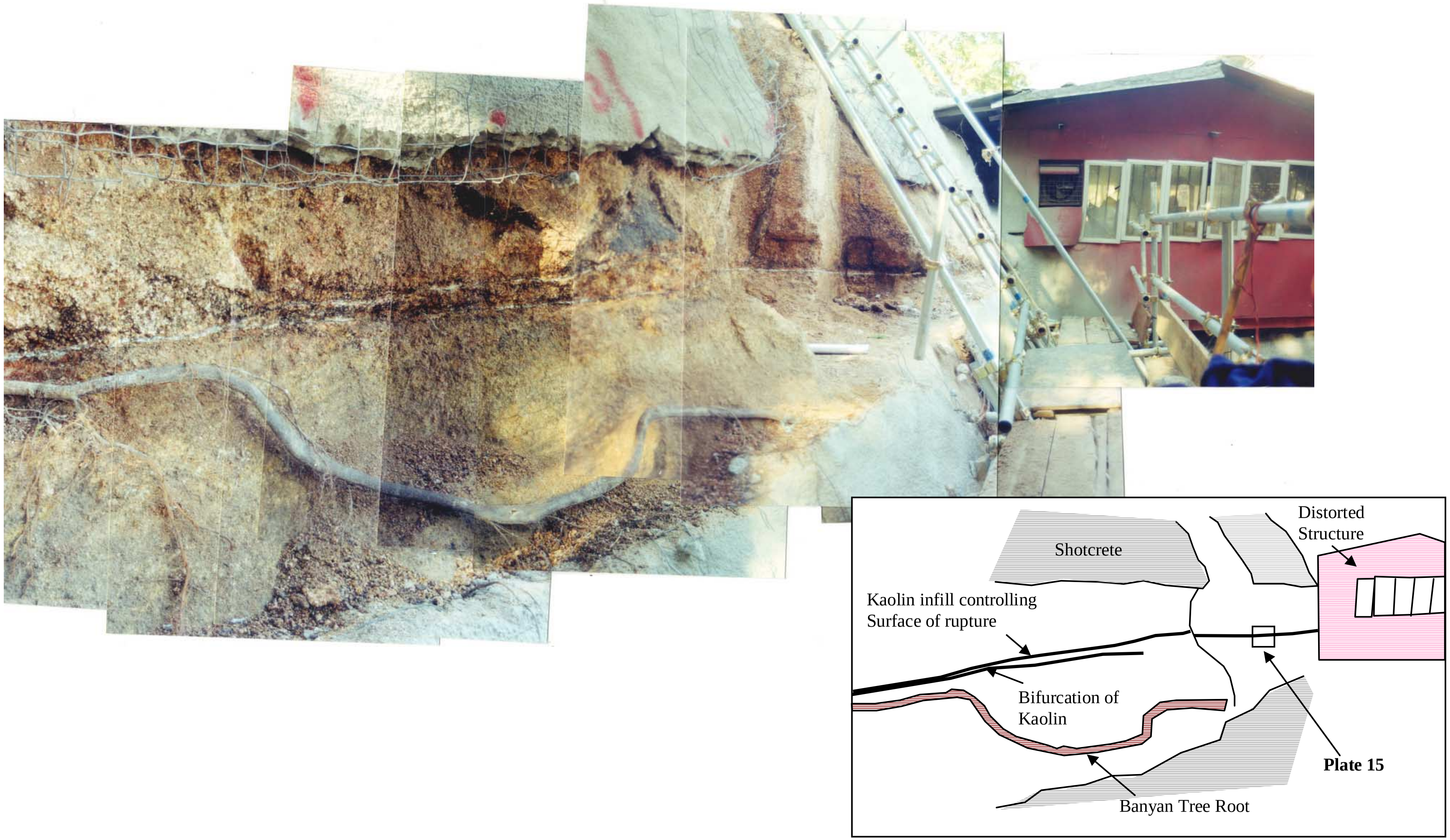


Plate 14 - Kaolin Infill Controlling Surface of Rupture, Southern Distressed Zone, Shek Kip Mei Landslide Site (1999)

Plate 15 - Close-up of Feature Shown in Plate 14 - the Dark, Planar, Horizontal Feature within the White Kaolin Infill Is the Surface(s) of Rupture of the 1999 Landslide

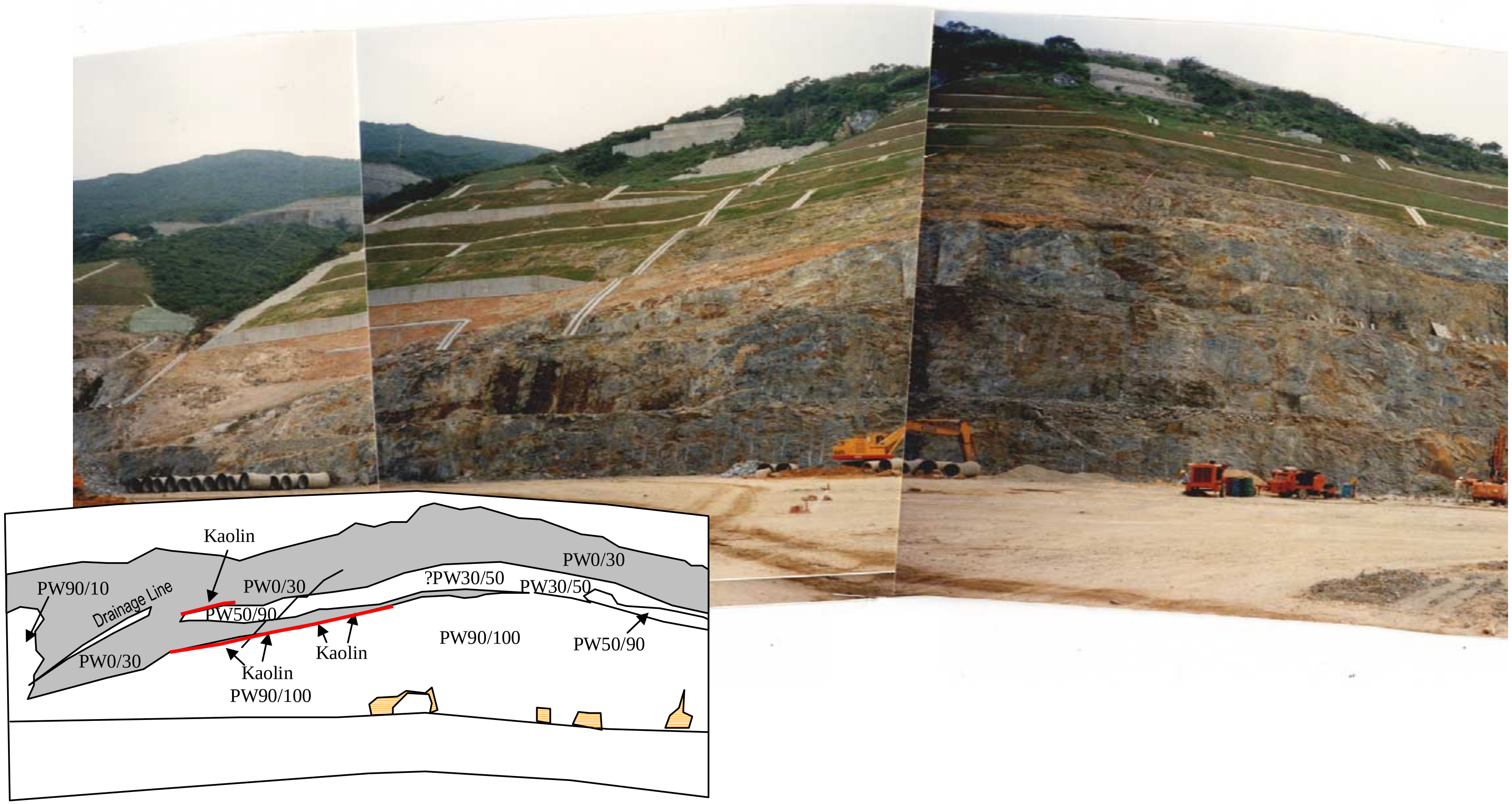


Plate 16 - Southwest Side of Siu Sai Wan Estate during Site Formation Showing Abrupt Interface in Weathering Profile between PW90/100 Rock Mass below and PW0/30 Rock Mass, above Which Kaolin Mainly Occurs

Plate 17 - Siu Sai Wan Estate during Site Formation (Precise Location Uncertain) Showing Probable Kaolin Distributed Immediately above the Interface between PW90/100 Rock Mass below and PW0/30 Rock Mass above

Plate 18 - Kaolin beneath Coreslab on West Side of Tiu Keng Leng Estate, during Site Formation (1999)

Plate 19 - Sedimentary Breccia with Kaolin Clasts, Extracted from Joint Infill, West Side of Tiu Keng Leng Estate, during Site Formation (1999)

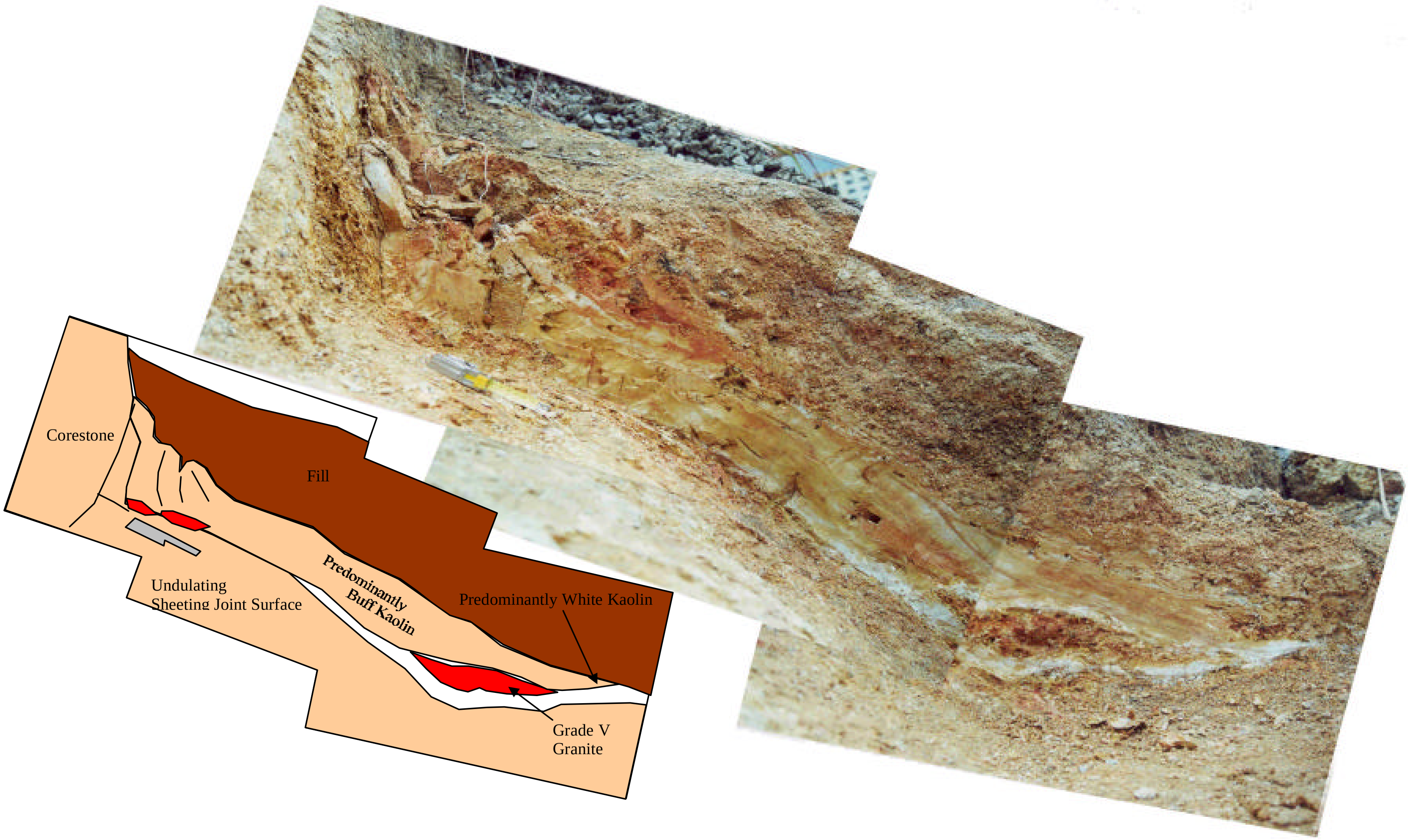
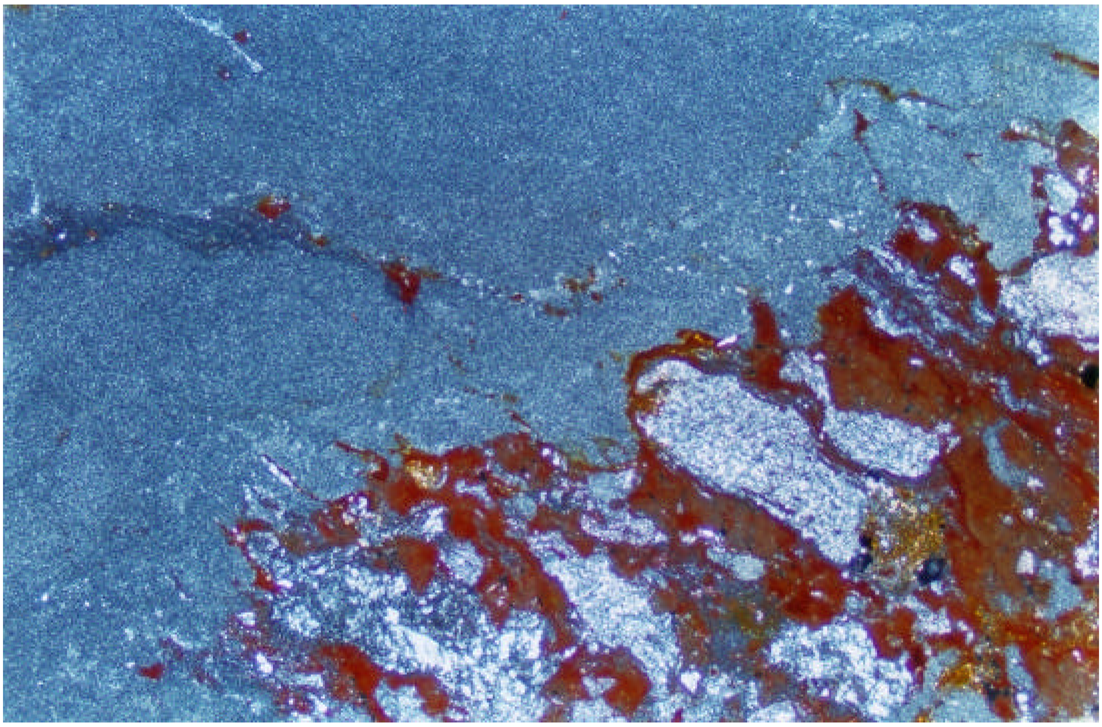


Plate 20 - Kaolin Infill Exposed in 2001 during Landslip Preventive Measures Works at Cut Slope No. 11NW-A/CR9



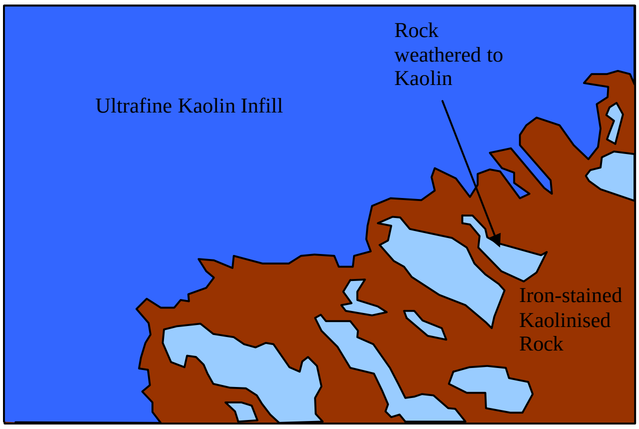


Plate 21 - Irregular Kaolin Infill and Contact with Saprolite Suggesting Penetration of the Kaolin from the Discontinuity into the Saprolite. Width of View 6.35 mm