The Significance of Primary Volcanic Fabrics and Clay Distribution in Landslides in Hong Kong

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Abstract: Most rain-induced landslides on Hong Kong's volcanic rocks are shallow and small-scale. However, two major landslides that occurred on Hong Kong Island in 1995 highlight relationships between primary volcanic foliations and kaolin accumulations that may have general significance in determining loci of larger failures. In the first case, a bedding-parallel shear zone was the locus for kaolin concentration in a shallowly dipping tuff. This formed a weak, planar, low-permeability layer which acted as the surface of rupture of a translational failure. In the second case, steeply inclined fabrics (eutaxitic foliations) and subparallel, closely spaced joints occurred within a zone of syn-volcanic folding and shearing. Deep weathering developed along the zone, with kaolin concentrations present mainly above the soil-rock interface. The irregular and variably concave to planar rupture surface was closely associated with kaolin-infilled relict joints towards the base of the soil profile. Kaolin distribution is largely associated with the weathering profile, and may have been both physically and chemically redistributed within it. Halloysite is more abundant than kaolinite in most clay samples at and near both rupture zones, and may have developed from kaolinite in response to strain. Detailed mapping of volcanic fabrics around the major landslides suggests that kaolinized bedding-parallel shear zones are uncommon, but that deep weathering zones associated with shearing and faulting are common, mappable features.

Keywords: landslides, eutaxitic foliation, halloysite, kaolinite, shearing.

On 12 and 13 August 1995, torrential rain fell on Hong Kong Island following the passage of Typhoon Helen close to Hong Kong. More than 70 slope failures were triggered (Wong 1996). Most of these were shallow and small-scale, typical of the rain-induced landslides affecting man-made and natural slopes on the steep, granitic and volcanic saprolite terrain of Hong Kong. Two of the landslides (Figure 1), however, were both large and deep-seated. They occurred within a few hours of each other early on 13 August. The first, at Fei Tsui Road, in the Chai Wan district on eastern Hong Kong Island, released some 14 000 m^3 of debris, killing one person and injuring another. The second, at Shum Wan Road, Aberdeen, in southern Hong Kong Island had a volume of 26 000 m^3, the largest Hong Kong landslide in 20 years, and caused two fatalities, five injuries and substantial damage to property. Both landslides were subjected to detailed forensic studies by the Geotechnical Engineering Office (GEO 1996*a, b*), the work commencing within hours of each incident. Independent geotechnical reviews into the two landslides were also carried out (Knill 1996*a, b*).

The landslides occurred in partially weathered volcanic rocks comprising predominantly fine ash tuff. Neither site has well developed bedding, but eutaxitic foliation is moderately to well developed at both. Lenses or seams of kaolinitic clay associated with discontinuities were identified as significant factors contributing to the failures. The occurrences of kaolin at each site, their contrasting settings in relation to volcanic fabric and weathering profiles and their inferred influence on slope stability are described in case histories below.

Further follow-up work was conducted by the GEO to determine whether other slopes near the landslide sites might contain similar geological features, or have similar geological settings. An initial review (Strange 1996) proposed studies in areas around Chai Wan and Aberdeen (Figure 1), encompassing the initial failure sites. Geological aspects of these studies (Campbell & Koor 1996; Franks *et al*. 1997) are described below, as are mineralogical and microtextural studies of clay samples from the two landslides (Merriman & Kemp 1995; Merriman *et al*. 1996).

Where deep-seated failures have occurred elsewhere in Hong Kong, adverse jointing/relict discontinuities and alteration (weathering or hydrothermal) have been identified as influences on the failure (e.g. Irfan & Woods 1988; Ho & Evans 1993; Irfan 1994 and references therein). Many of these failures in volcanic rocks are similar to the landslides reported here. For example, several features discussed below at the Shum Wan Road landslide near Aberdeen, were described (Irfan 1994) at the landslide in 1988

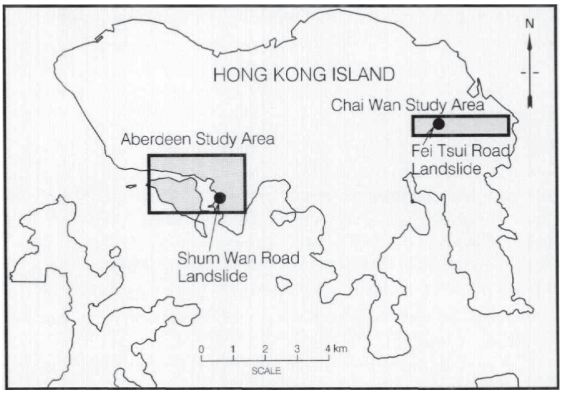

Figure 1. Location diagram showing the Fei Tsui Road and Shum Wan Road landslide sites, and Chai Wan and Aberdeen study areas

behind Island Road Government School in Aberdeen. However, until now, no specific relationships to primary volcanic fabric have been reported. Descriptions of material and mass decomposition in this paper follow usage proposed by the Geotechnical Control Office (GCO) (1988).

Figure 2. Oblique aerial photograph (17/8/95) showing the Fei Tsui Road landslide site

CASE HISTORY 1: FEI TSUI ROAD LANDSLIDE (FIGURE 2)

The landslide occurred in a soil and rock cut-slope above Fei Tsui Road in Chai Wan. The slope, formed in the mid-1970s in relation to an adjoining housing development, was 200 m long and obliquely truncated a spur line on which a salt-water reservoir had been constructed in 1959. The 70° cut-slope had a bench just above half-height, drainage channels, and chunam (cement-lime stabilized soil) cover on exposed soil. Photographs show that by 1994 the slope lacked maintenance and had a considerable unplanned vegetation cover. At the time of failure, surface drains were completely blocked by organic debris (GEO 1996*a*).

The failure occurred at the highest part of the cut-slope (*c*. 30 m) along a section about 50-60 m long. The main scarp was 15 m behind the original cut-slope crest and the depth of the failure averaged 15 m. Debris travelled up to 70 m, and spread out to a maximum width of 90 m (Figure 2 and GEO 1996*a*). Subsequent remedial work has extensively modified the site.

Solid geology

The site is underlain by variably decomposed, lapilli-bearing, fine ash vitric tuff. Eutaxitic foliation, highlighted by fiamme but best seen in thin section, dips at 10-20° to the N or NW (Figure 3), almost directly out of the cut-slope. The tuff was included within the Shing Mun Formation on the Hong Kong Geological Survey (HKGS) 1:20 000-scale geological map of the area (GCO 1986) but has recently been reassigned to the younger (Cretaceous) Che Kwu Shan Formation (Campbell & Sewell this volume).

The landslide site is < 100 m from the contact with a major (10 km diameter) granite pluton. The contact dips under the site, so granite may underlie it at depth. The volcanic rocks are strongly hornfelsed near the contact. Lesser contact metamorphic effects can be seen in thin sections from the landslide site (Merriman & Kemp 1995).

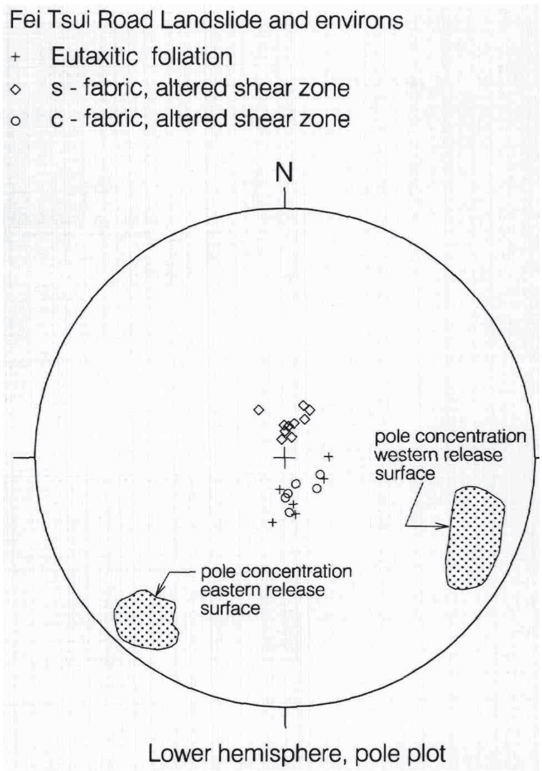

Figure 3. Stereoplot (equal-area, lower hemispheric) of poles to eutaxitic foliation, S- and C-shear fabrics and major joint sets at the Fei Tsui Road landslide site

The weathering profile varies across the site. Completely decomposed volcanic rock is <5 m thick in the east, close to the crest of the original spur-line, but up to *c*. 12 m thick in the west. In the east and centre of the failure, completely decomposed rock overlies several metres of moderately decomposed volcanic rock. Fresh to slightly decomposed volcanic rock forms the lower part (up to 8 m high) of the cut-slope (directly below completely decomposed rock in the west of the failure).

Two major sets of persistent, steep, planar, close to medium spaced joints occur across the site. They controlled the eastern and western release surfaces (dipping respectively 80° to 290° and 70° to 045°). The 'saw-tooth' main-scarp was formed from a combination of these joint sets. Small displacements occur on some west-dipping joints. Weak completely decomposed volcanic rock lies directly behind joints in the upper slope. Kaolin concentrations occur along some faults.

Kaolin-rich layer

A key geological feature of the site is a shallowly inclined, sheared layer of kaolinized and kaolin-veined, highly to completely decomposed tuff. The layer dips at 10-20° to the N or NW across the entire site, and formed the surface of rupture in the east. The feature is present, but less well developed, in some boreholes south, east and west of the site.

Figure 4. View NW towards the cut-slope at Fei Tsui Road during site formation (1977): dark band in middle of face is the kaolin-rich layer; chunam on slope covers soil.

The layer is generally a distinctive pale yellowish-white. Although highly kaolinized (up to 70%), the original volcanic texture remains visible and eutaxitic foliation is evident in thin section. Well-developed S-C fabrics define a shear zone co-planar with the eutaxitic foliation. The C fabric is parallel to closely spaced joints infilled with kaolin (sometimes with slickensides) and Mn-oxide (todorokite) coatings. The S fabric is parallel to kaolin veins up to 20 mm thick. The layer is offset by minor north-trending faults, which downthrow to the east, mostly by < 1 m, but in one instance near the middle of the landslide, by 2-3 m.

In the central and eastern parts of the failure, the layer, now largely removed during remedial works, occurred within moderately to highly decomposed volcanic rock (PW50/90), was thin (0.5 m), highly kaolinized with very abundant kaolin veins, and was intimately associated with the surface of rupture. Landslide debris generally lay directly above the (partially eroded) layer. A photograph taken during site formation shows the same layer daylighting about 8 m above road level (Figure 4).

West of the failure, the layer occurs within completely decomposed volcanic rock, is more 'diffuse', relatively thick (3 m), less intensely kaolinized, and though predominantly of highly to completely decomposed, includes some moderately decomposed rock. Clay lenses and veins are less abundant, and most occur near the top of the layer. In the west, the failure truncated the layer near the base of the western release surface. The surface of rupture formed here at the abrupt interface between completely (PW 0/30) and slightly decomposed or fresh tuff (PW 90/100), which was virtually co-planar with the kaolin-rich layer to the east. The geometry and distribution of materials and features are shown in Figures 5-7.

Microtextures indicate multiple phases of kaolinization (Merriman *et al.* 1996), Mn-oxide deposition and deformation within the altered layer. These are thought to have occurred relatively recently due to weathering processes. However, the shear zone that localized the kaolinization is an ancient, if not syn-depositional, structure that was offset by faulting which may have been associated with intrusion of the nearby pluton. In this scenario, hydrothermal fluids may have initiated alteration within the shear zone.

Groundwater

Records of seepage in earlier site reports suggest that the normal groundwater level lay within the band of fresh rock at the base of the cut-slope. However, observations suggest that a temporary perched water table developed on top of the relatively impermeable clay-rich layer during the heavy rain prior to the failure (GEO 1996*a*).

Landslide debris

The landslide debris, now largely removed, mainly comprised coarse gravel to boulder-sized, joint-bounded blocks of moderately and highly decomposed volcanic rock in a matrix of sandy clay. The proportion of rock to soil matched the variation in the cut-slope before failure, with far more rock on the east side of the debris fan. One block of slightly decomposed tuff was at least 50 m^3 in volume.

Mechanism of failure

The GEO (1996*a*) concluded that the principal factors that caused the landslide were: the presence of the laterally extensive kaolinite-rich altered tuff layer which formed a weak and impermeable layer, and enabled development of a deep translational failure mechanism; and an increase in groundwater pressure, after prolonged heavy rainfall caused a perched water table to form above the altered tuff layer. Several small failures predated the major failure in 1995. Photographs and notes of landslides in 1987 and 1993 (GEO 1996*a*) show small-volume failures with surfaces of rupture coincident with the kaolin-rich layer.

CASE HISTORY 2: SHUM WAN LANDSLIDE (FIGURE 8)

Solid geology

The site, mapped previously at 1:20 000-scale by the GCO (1987), mainly comprises eutaxitic fine ash vitric tuff of the Ap Lei Chau Formation of lowermost Cretaceous age (Davis *et al.* this volume). The formation crops out widely on southern Hong Kong Island and in east Hong Kong. W- to WNW- trending, open folds are developed in the area.

Commonest lithologies on and around the site (Figure 9) are fine to coarse ash eutaxitic tuff, lapilli- and block-bearing tuff and tuff breccia. Matrices comprise finely recrystallized vitric tuff. Crystals (up to 10% of the rock) of feldspar and quartz, are mostly < 3 mm in size. The tuffs vary from scarcely altered to extensively kaolinized, some alteration (contact metamorphism) predating kaolinization (Merriman & Kemp 1995).

Eutaxitic foliation is common, the fiamme (tens to hundreds of mm in size) being flattened, chloritized and kaolinized pumice. Lithic lapilli also commonly show a preferred orientation, but larger lithic blocks (up to 400 mm) are more irregular. The eutaxitic foliation on the landslide scar dips much more steeply than in the surrounding area. In the upper part of the scar,

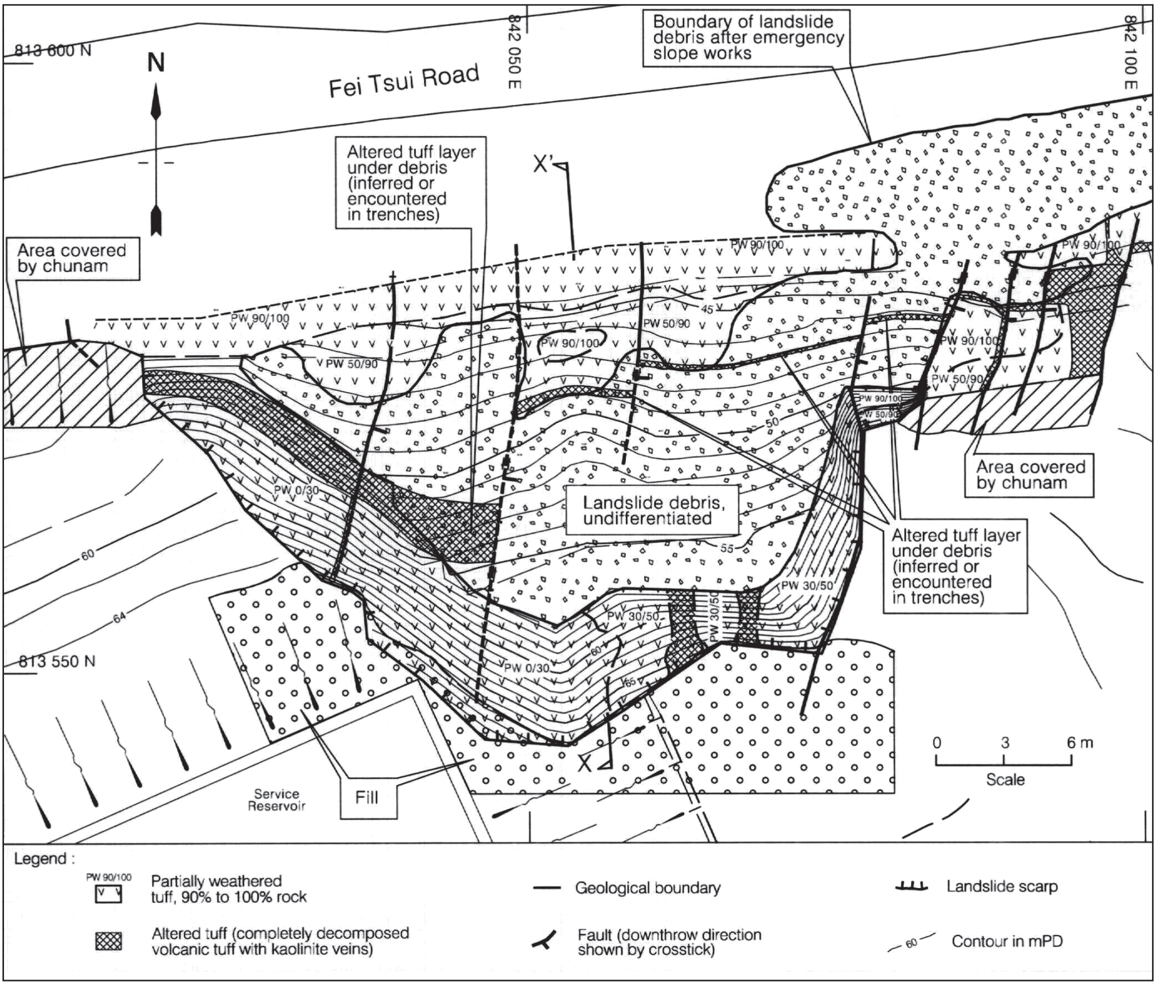

Figure 5. Geological map of the Fei Tsui Road landslide site (modified from GEO 1996*a*)

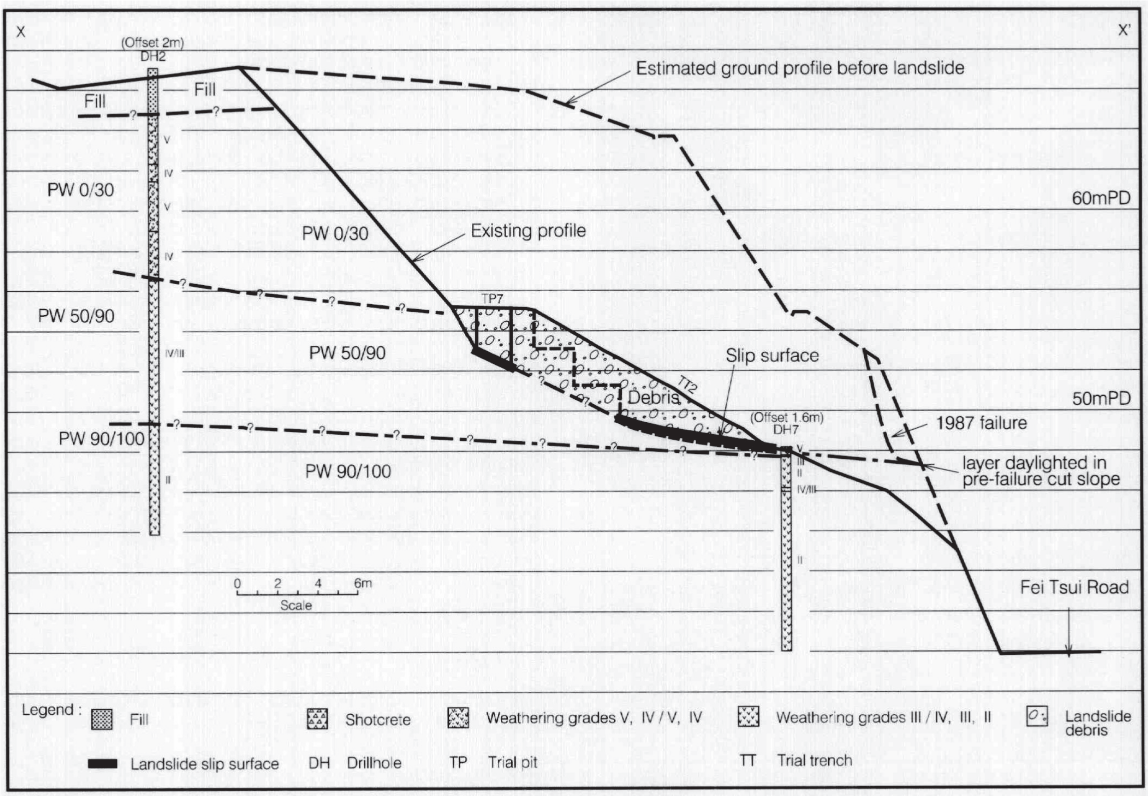

Figure 6. Geological cross-section of the Fei Tsui Road landslide. See Figure 5 for location (modified from GEO 1996*a*)

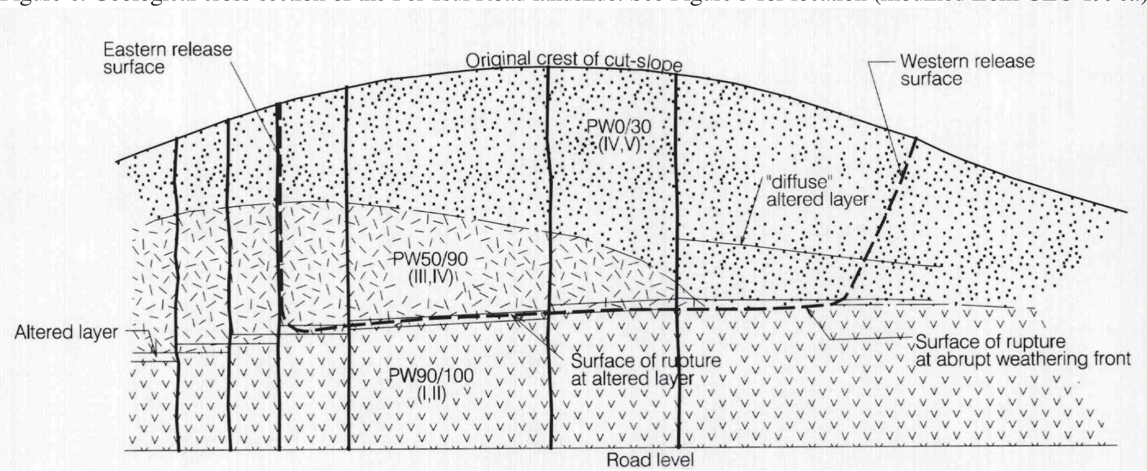

Figure 7. Sketch transverse section with inferred pre-failure geology of the cut-slope at Fei Tsui Road, showing the weathering (by rock mass), the kaolin-rich layer, and the surface of rupture of the landslide

foliation is commonly very steeply inclined (70-90°) or locally overturned (80-90°), and strikes similar to, but slightly more NNW than the WNW-trending landslide scar (Figures 10 and 11). Outside the scar, the foliation is more shallowly inclined (15-40°). The northern margin of the zone of steep foliation coincides with an increase in the size of the fiamme and reduction in the material weathering grade. In the lower part of the landslide site, eutaxites are also steeply inclined but strike more northerly. The steep foliation zone is interpreted as a shear zone and, or, a tight monocline. A slickensided fault at the rear of the landslide scar dips at 78-90° to the SSW or *c*. 80-90° to the NNE, and separates rock (PW90/100) to the NNE from soil (PW30/50) to the SSW. The fault lies along the northern limit of the zone of steep eutaxitic foliation.

Joints and joint infills. Joint orientations at the landslide site are similar to those in the surrounding area. However, extremely to very closely and closely spaced joints occur within the zone of steep eutaxitic fabric in the upper part of the landslide scar. Elsewhere around the site, this joint set is closely to widely spaced, and dips very steeply to the SW. Another widespread subvertical joint set (closely to widely spaced) strikes NW-SE, but steeply inclined joints of other orientations are sporadic. Shallowly inclined (20-35°) joints (closely to medium spaced), interpreted as stress release joints, dip to the NW or W, as do the prevailing slope and the landslide surface of rupture. Other local, shallowly inclined joints dip to the SSW and E.

Close below the surface of rupture, joints are generally coated with todorokite (Mn-Ca-Ba-oxide) and commonly, but variably infilled with white and buff kaolin up to 20 mm thick. Sporadic, fissure-like joint infillings of soft, moist, buff, sandy kaolin, are up to 230 mm thick, but taper sharply downwards. These deposits also occur in shallowly inclined joints. In places, tabular fragments of white kaolin, detached from adjacent joint walls, occur within buff kaolin which resembles that along and above the surface of rupture. The complexity of joint infillings implies protracted minor movements, possibly related to near-surface creep prior to the main failure. These caused repeated openings of joints which were then infilled, physically with, or by precipitation of kaolin, and by Mn-oxide (see Figure 14b).

Weathering depth and abundance of kaolin-filled joints are both greater at the landslide site than to its north and to a lesser extent its south. Kaolin-filled subvertical and shallowly inclined-joints, up to tens of mm thick, are common just below the surface of rupture in the upper part of the site (Figure 9). However, in adjoining road sections, mostly in rock, kaolin-filled joints were rarely seen.

Colluvium

The original slope at the landslide site was covered by thin colluvium, 0.5-1.5 m thick. Outside the site, the layer comprises dense to very dense, light yellowish-brown, clayey, silty, fine sand to clayey, sandy silt with 20-35% volcanic clasts mottled red, brown and white, subangular, highly to moderately decomposed gravel and cobbles.

Colluvium samples from near the site (GEO 1996*b*) were dated by thermoluminescence and gave late Pleistocene ages of 34 800 ± 2800 a BP, 48 200 ± 3900 a BP, and 43 600 ± 3500 a BP (analysis by Professor Shen Chengde, Institute of Geochemistry, Guangdong, Chinese Academy of Sciences). These may indicate ages of previous slope failure.

Figure 8. Aerial view of the Shum Wan Road landslide on the day (13/8/95) it occurred

The surface of rupture

The zone of the surface of rupture (now largely removed) comprised (from top to base) the following.

(a) Landslide debris.

(b) Soft, moist, white buff and brown, mottled sandy silt/clay *c*. 10-100 mm thick (max. 350 mm), containing subangular tuff clasts (grade II-IV) of sand to gravel size, with shear planes subparallel to the underlying kaolin layer (c), or undulose, sigmoidal and irregular, due to rotation during downslope movement.

(c) Soft, moist, white kaolin, up to 15 mm thick, above a Mn-coated, moderately inclined joint. Kaolin is thickest where the joint is offset (up to c. 20 mm) across sheared subvertical joints (Figure 12). Slickensides and sigmoidal shear fabrics (cf. S-C fabrics), are consistent with downslope movement of overlying material. The kaolin contains: sheared Mn-oxide, subangular, fine sand of decomposed tuff, and tabular white kaolin fragments.

(d) Moderately to highly decomposed volcanic rocks (grades III-IV), with closely to very closely spaced subvertical and moderately inclined joints (in situ rock/soil).

The surface of rupture was associated with shearing along one or more planes, in a relatively thin zone. Shear-coupling and duplexing occurred across this zone (up to 350 mm thick, but usually < 100 mm) comprising white kaolin and buff sandy kaolinitic silt/clay.

The upper slope had a concave surface of rupture related to rotational detachment and disaggregation of a sequence 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.

Landslide debris

The landslide deposits, up to 5 m thick, comprise

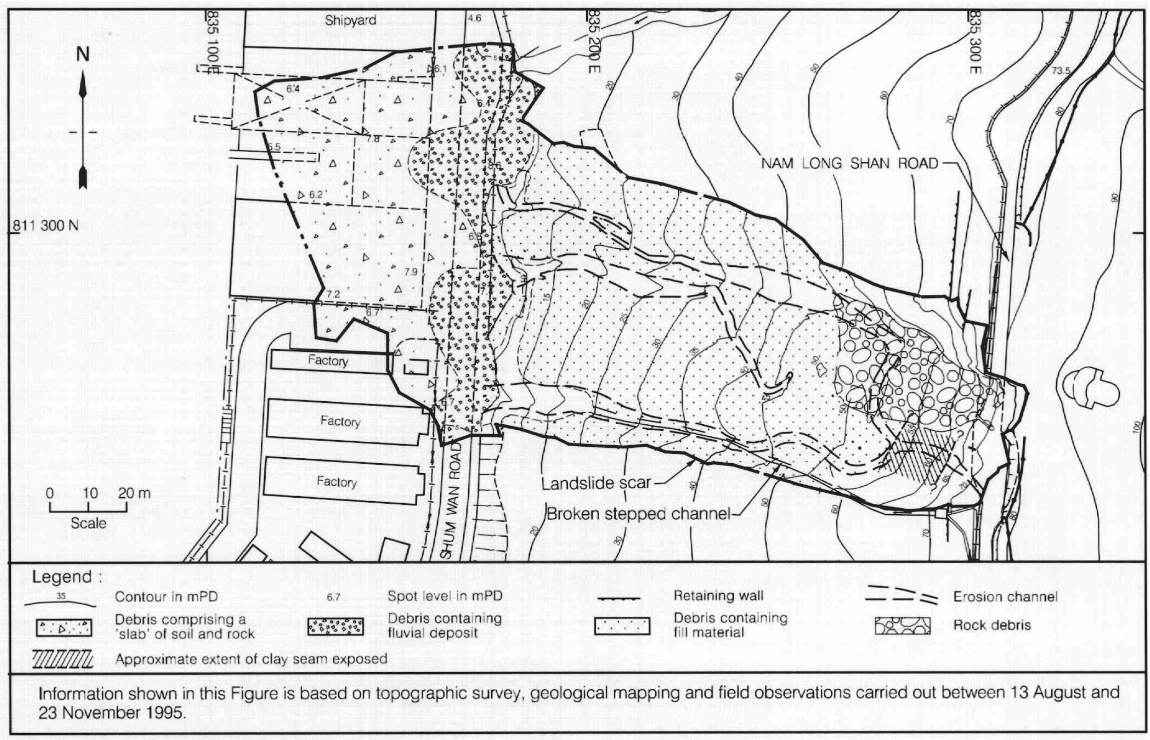

Figure 9. Geological plan of the Shum Wan Road landslide (modified from GEO 1996*b*)

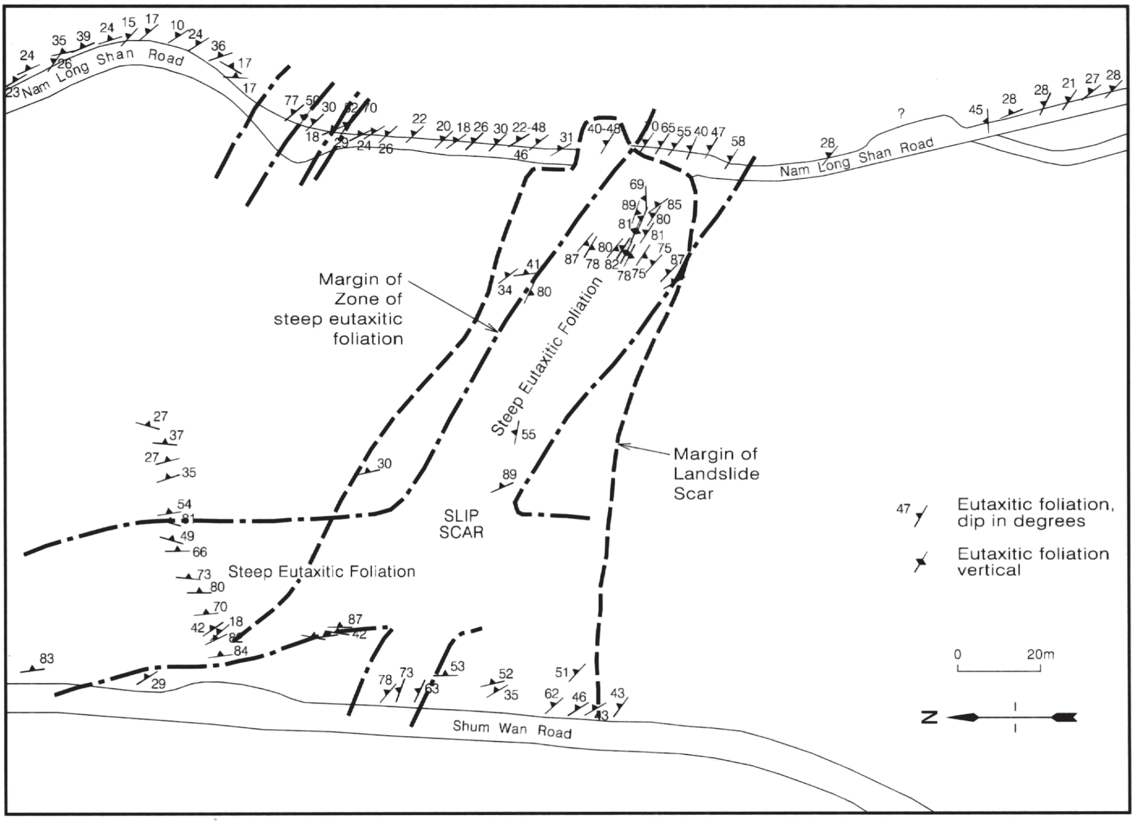

Figure 10. Map showing variation of eutaxitic foliation around the Shum Wan Road landslide

sandy silt/clay, with gravel, cobbles and a few boulders, varying to matrix-poor debris of large rafts, up to metres across, comprising highly decompressed to completely decompressed volcanic rocks with relict joints. Hence, the debris comprises mainly saprolitic soil with some rock, colluvium, topsoil, vegetation and fill.

A large section derived from the rear of the landslide, incorporating a mainly intact section of Nam Long Shan Road, was deposited *en masse* on the upper scar. The bitumen peel surface dipped at *c*. 12-14° towards the hillside, indicating its rotational emplacement. Rockfall debris comprising joint-bounded boulders, mainly from the NE of the main scarp, partly filled the depression above the rotated block about half an hour after the main failure (GEO 1996*b*).

Slabs of debris, tens of metres or more across and 2-3 m thick, were deposited west of Shum Wan Road (Figure 9). They largely preserved the stratigraphy of the upper soil profile of the slope. Vegetation, topsoil and fill were probably bulldozed in front of the slabs during emplacement and continually overridden by them. Detachment of the slabs may have been selective along kaolin-rich horizons seen in the soil profile.

Secondary modification of the landslide site

After the main failure, the landslide site was extensively modified by minor failures and remobilization of landslide debris as mass flows, and by fluvial erosion and redeposition mainly near the slope base. Springs issued from points along the main scarp, and persistent seepage from a clay layer in the SE of the site indicated the presence of perched water.

Important geological features of the landslide site

Geological factors possibly contributing to the scale and form of the landslide, include the following:

(a) Subvertical eutaxitic foliation, striking subparallel to the slope and to steep, very closely spaced joints, and a fault. These structures concentrated downslope movement of ground water, and led to the formation of a deeply weathered zone.

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

(c) Thick silt/clay with weathered tuff clasts along shallowly inclined stress release joints and associated with shearing due to downslope movement (?creep).

(d) Subvertical joints that acted as release surfaces.

However, these features are additional to man-made influences that triggered the landslide (GEO 1996*b*), including: initial failure of a fill embankment that caused concentration of water onto the rear of the landslide site from Nam Long Shan Road; and

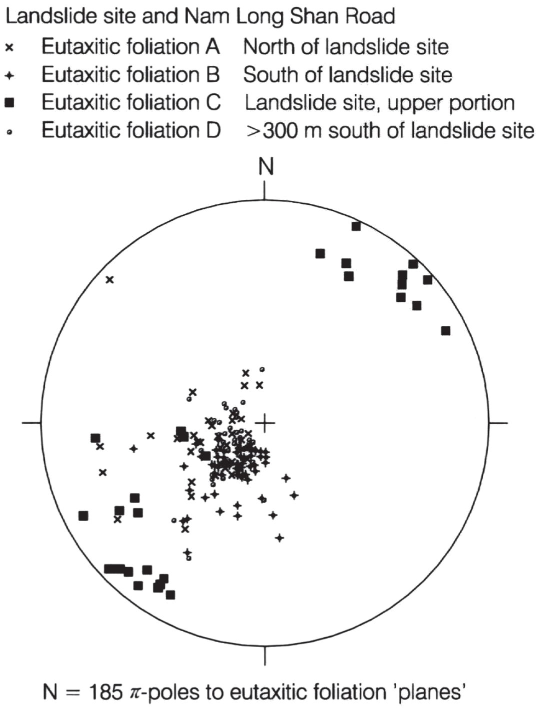

Figure 11. Stereoplot (equal-area, lower hemispheric) of poles to eutaxitic foliation at Shum Wan Road landslide site, and to its north and south along Nam Long Shan Road.

inadequate maintenance and blockage of the drainage system at and below Nam Long Shan Road.

FOLLOW-UP STUDIES TO THE TWO LANDSLIDES

Follow-up studies were undertaken around the two landslide sites (Chai Wan, Campbell & Koor 1996 and Aberdeen, Franks *et al*. 1997) to assess the prevalence of the geological features thought to have influenced development of the landslides and then to identify cut-slopes in which such features occur. The features of specific concern were:

(a) thick (hundreds of millimetres) and laterally extensive (tens of metres) concentrations of kaolin in impermeable and weak layers within rock masses;

(b) completely to highly decomposed (grade IV/V) tuff along relatively planar rock seams that sit on slightly to moderately decomposed tuff (grade II/III), that dipped directly, or obliquely outward from rock slope faces at angles of >*c*. 20°;

(c) stratified or foliated volcanic rocks, dipping directly, or obliquely outward from rock slope faces, at angles of >*c*. 20°;

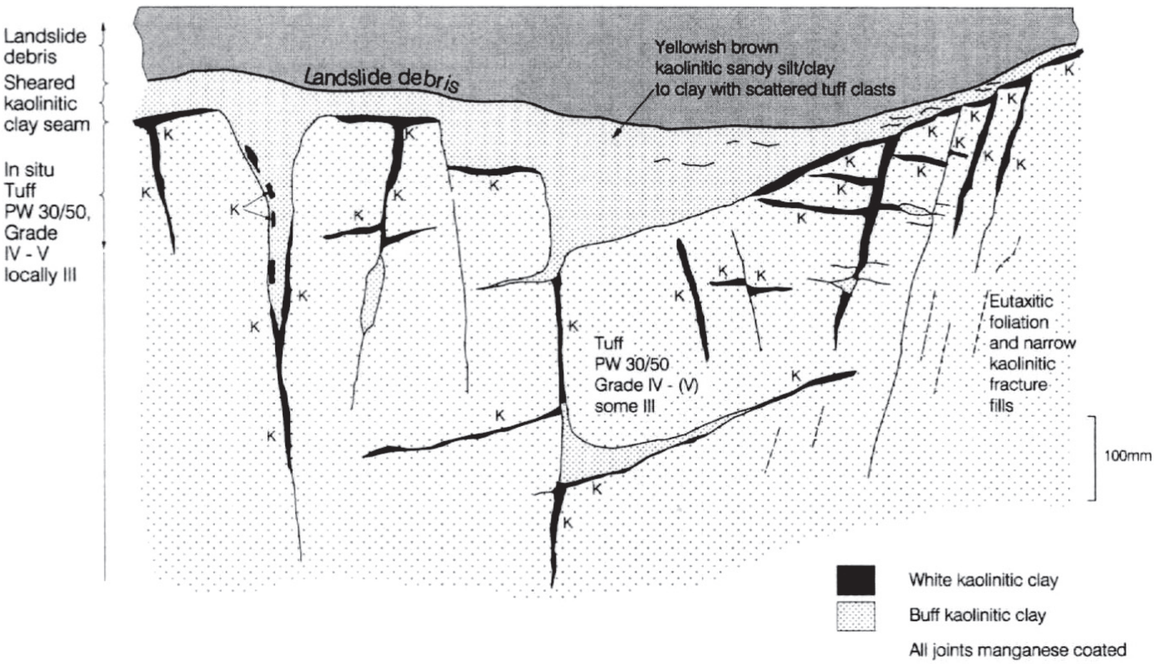

Figure 12. Schematic representation of surface of rupture at the Shum Wan Road landslide

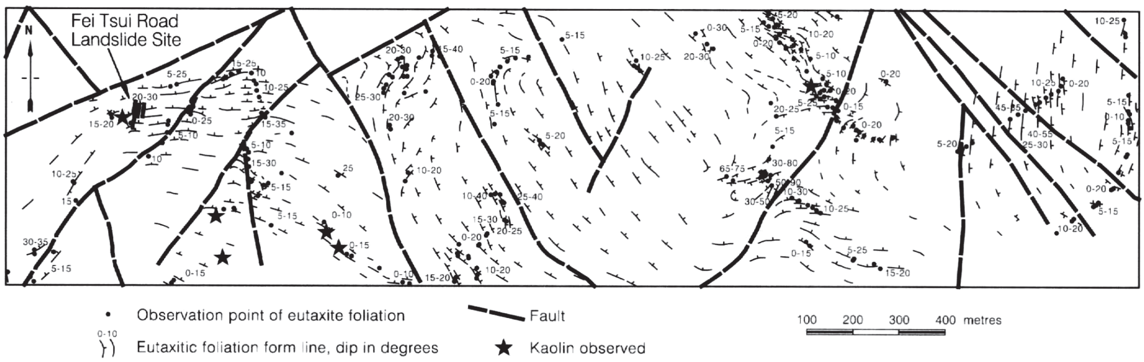

Figure 13. Eutaxitic foliation form lines and major faults in the Chai Wan study area

(d) stratified or foliated volcanic rocks with steep to sub-vertical dip, striking sub-parallel to the local slope direction;
(e) persistent, closely to medium spaced, tight and rough, planar, steep (>60°) joint sets that could form release surfaces;
(f) zones of deep weathering and associated kaolinitic clay seams.

Circumstantial evidence for some of these features was also gathered, including identifying zones of continuous seepage, and clusters of previous slope failures. Aerial photograph interpretation was used to identify relict landslide features.

Geological surveying (1:1000-scale) focused on identifying the orientation of eutaxitic foliation, and stratification in general, in the dominantly eutaxitic fine ash vitric tuff of the two study areas. These planar features provided the best way to identify cut-slopes that could contain adversely orientated bedding-parallel features, as at the Fei Tsui Road landslide, but where the features are obscured by protective covering (chunam, shotcrete etc.). The survey also recorded joints, faults, the distribution of kaolin and its relationship to material weathering grade.

Volcanic fabric mapping

Chai Wan area. Detailed mapping of eutaxitic foliation (Figure 13) revealed domains within which the foliation is shallowly inclined to the N, NE and E, separated by relatively narrow, linear fault zones, trending NE-SW and NW-SE, within which steeply inclined to subvertical foliation is more typical. Some of this faulting may have occurred during emplacement of the tuffs (Campbell & Sewell this volume). Most of the cut-slopes dip the same direction as the prevailing

N-, NE- and E-dipping natural slopes, and given the predominance of N-, NE- and E-dipping eutaxitic foliation, there would be a high likelihood that bedding-parallel structures, similar to that at the Fei Tsui Road landslide site, would be adversely orientated with respect to cut-slopes (Campbell & Koor 1996).

Aberdeen area. A broadly similar structural pattern to that in Chai Wan was identified, though ENE-trending fold axes are more prevalent and steeply inclined foliation is more common. However, although lithological variation is common, there are few cut-slopes in the area that contain adverse orientations of bedding (Franks *et al*. 1997).

Adverse geological features

Chai Wan area. Some cut-slopes have similar lithology and structure to the Fei Tsui Road landslide site and contain laterally persistent kaolin seams within shallowly inclined discontinuities that dip adversely out of the slope. No kaolin seams of comparable thickness to that at the Fei Tsui Road landslide were recognized. In part this reflects poor development of stratification in the volcanic succession around Chai Wan. Most observed clay seams, except those in subvertical discontinuities, were associated with discontinuities dipping 10° or less. However, slopes that contain adversely-dipping seams of kaolinitic clay, or highly decomposed material with a significant kaolin component, do occur, especially at, and above, the interface between the PW90/100 to PW0/30 rock mass weathering zones. This interface commonly occurs at a planar discontinuity which is generally interpretable as a stress release joint.

Aberdeen area. The main faults trend ENE and NNW and are typically zones of deeper weathering. Superficial deposits tend to be thicker above these fault zones also. Where they are associated with deep weathering striking subparallel to the downslope direction, an important geological condition similar to that at the Shum Wan Road landslide occurs. Some planar or trough-shaped adversely-orientated discontinuities occur at, or within 5 m of, the PW90/100 to PW0/30 rock mass weathering zone interface. These may be loci for preferential kaolin accumulation (and seepage) which can be laterally continuous, as at the Fei Tsui Road landslide site. This style of weathering of the fine ash vitric tuffs differs, as in the Chai Wan area, from the corestone profiles often regarded as typical in Hong Kong. Some natural slopes in the Aberdeen area that lack significant soil profiles appear to do so because the soil has been removed during slope failure. Hence, adjoining areas on which the soil is retained may form slightly elevated spurs.

Closely to widely spaced subvertical joints, especially parallel to the main faults, are virtually ubiquitous in both areas, so that release surfaces, similar to those at the Fei Tsui Road landslide, could occur in most cut-slopes.

Kaolin mineralogy and microtextures

At the two landslide sites, kaolinite group minerals are abundant, both in the altered tuffs as a replacement of the matrix and feldspar phenocrysts, and as fracture- and vein-infillings. Slip surfaces developed preferentially along zones of abundant kaolin-filled veins and fractures. These clays were investigated using X-ray diffraction (XRD) analysis, optical petrography and scanning electron microscope (SEM) techniques (both scanning and backscattered electron imaging modes; Figure 14). Details of equipment used, sample preparation methods, and XRD analysis and interpretation are contained in Merriman & Kemp (1995) and Merriman *et al*. (1996).

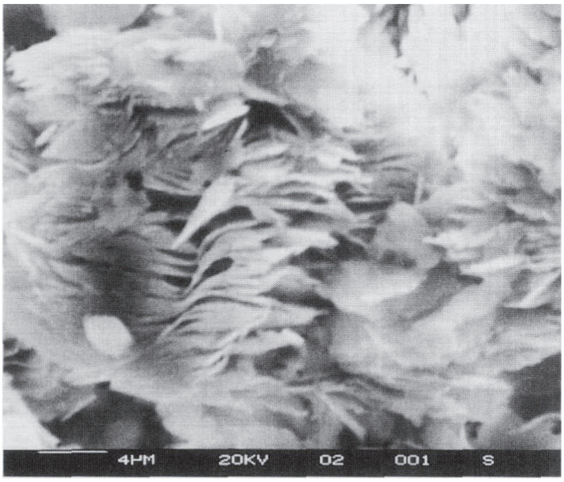

Figure 14a. Fei Tsui Road: backscattered secondary electron photomicrograph of crenulated books of kaolinite crystals in white clay vein below surface of rupture

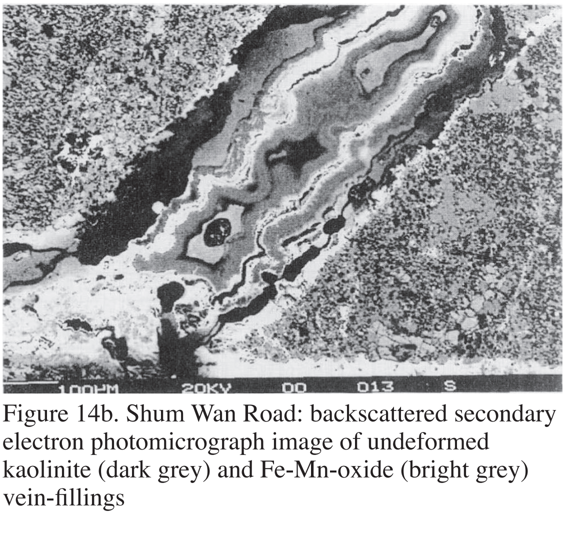

Figure 14b. Shum Wan Road: backscattered secondary electron photomicrograph image of undeformed kaolinite (dark grey) and Fe-Mn-oxide (bright grey) vein-fillings

XRD analysis

XRD analysis of clay samples suggest there are differences in the relative abundances of the two kaolin minerals, kaolinite and halloysite, between the two landslide sites (Table 1). Halloysite is generally less abundant at Fei Tsui Road than at Shum Wan Road. Todorokite and other Mn, Fe, Ba-oxides generally form linings of joints.

At Fei Tsui Road, least altered samples of tuff contain the highest proportion of kaolinite and mica, but both decrease, and the proportion of halloysite increases, in more altered tuffs within the zone of abundant clay-infilled joints. Halloysite is the dominant kaolin mineral in the reddish brown slipped clay, but kaolinite is more abundant in white veins immediately below the slip plane.

At Shun Wan Road, halloysite forms up to 87% of some joint infills. It is the dominant clay mineral in very closely spaced, subvertical, clay-filled joints below the rupture, and forms 80% of the white clay along the surface of rupture (now largely removed), although kaolinite may have formed high proportions of clays on either side of the rupture. Traces of l0Å illite were common, but only traces of illite/smectite and discrete smectite were found.

SEM and other microtextural studies

In many samples, the kaolinite infillings were undisturbed, whereas others showed laminated wallrock linings deformed and folded in the infill. At the Shun Wan Road landslide, highly strained kaolin occurs in slip plane gouges associated with the surface of rupture. Typically, the gouge consists of fragments of kaolinized tuff in a matrix of micro-fractured and strained kaolin, indicating repeated movement. These textures develop in zones of abundant kaolin-filled fractures, some of which show evidence of wallrock brecciation. Multiple movement are also apparent at Fei Tsui Road. Some kaolin-filled joints formed as tensional fissures (Figure 14b) associated with shearing. The surface of rupture at Fei Tsui Road, and associated discontinuities, acted as conduits for mineralizing fluids.

Two morphological types of kaolin group crystals were identified using SEM. The most common comprise books of platy crystals. They may form elongate, vermiform crystal stacks that are typical of kaolinite. Less commonly, the platy crystals are overgrown by fibres. These resemble halloysite fibres imaged by Jeong & Kim (1993) and rods and laths of halloysite illustrated by Singh & Gilkes (1992). However, unequivocal tubular morphologies were not identified. The fibres may represent an early developmental stage of curved plates and laths of halloysite (Figure 14a), formed by *a*-axis roll (Singh 1996) as a result of strain affecting pre-existing flat kaolinite plates. Some fibrous halloysite also occurs locally on platy kaolinite crystals within veins lacking deformation microfabrics, implying a secondary origin.

The study confirms the observation of Tanaka (1992) that halloysite is typical of ‘rupture surfaces’ and is a key mineral in the development of landslides. Although the proportion of halloysite present prior to earliest movement on the surfaces of rupture is unclear, once movement was initiated, strain appears to have favoured further halloysite development at the expense of kaolinite.

DISCUSSION

The Fei Tsui Road and Shum Wan Road landslides were large-volume, deep-seated failures influenced by kaolin-infilled relict discontinuities. Forensic examinations of both landslides have provided valuable guidelines for identifying other locations where similar geological conditions may exist. In particular, structural geometry determined from the

Table 1. Estimated proportions of clay minerals by XRD analysis of sample fine-fractions from the Fei Tsui Road and Shum Wan Road landslide sites

Site	Description	Sample	% Kaolinite	% Halloysite	%‘Mica’
Fei Tsui Road	Clay-filled joints, altered zone	HK11885	41	52	6
	Altered zone	HK11886	35	51	14
	Brown clay	HK11889 B	62	36	2
	White clay	HK11889 W	29	64	7
	Clay vein	HK11891	24	46	30
	Least altered tuff	HK11894	57	19	24
	Brown clay	HK11896 B	32	57	12
	White clay-filled vein	HK11896 W	68	12	20
Shum Wan Road	Southern margin of landslip	HK11062	17	79	4
	Clay-filled joints	HK11073	7	91	2
	Clay-filled joint below slip	HK11077	11	87	2
	Buff/reddish clay	HK11895 B	90	3	8
	Clay-filled Joints	HK11895 V	69	19	12
	White clay on shear plane	HK11895 W	20	80	0

orientation of primary volcanic fabrics (eutaxitic foliation, bedding lamination, flow banding, etc.) can be a valuable indicator of adversely orientated features within slopes, and of steeply orientated shear zones that are loci of deep weathering zones.

Follow-up studies to the two landslides showed that primary volcanic fabric is mappable on a regional scale and often in considerable detail. Regional styles of structure defined by the volcanic fabrics persist across Hong Kong Island. Volcanic fabric maps can, therefore, be used to predict the bedding geometry of individual soil slopes. Deep weathering zones, related to fault and shear zones within which the fabric is steeply inclined, are readily identified, relatively common and have consistent orientations regionally. Shallowly inclined shear zones were not commonly observed, however, and there are few records of their occurrence, so that the type of feature that influenced the failure at Fei Tsui Road, is probably unusual. Accumulations of kaolin associated with the interface between the PW90/100 and PW0/30 rock mass weathering zones are more common. This interface is often planar, where associated with stress release joints, and adversely orientated.

Throughout both study areas, kaolin (kaolinite and halloysite) occurs within, or close to, the soil profile, and its distribution is thought to be related mainly to weathering. Hydrothermal alteration was a less important mode of kaolinization, but may be significant locally. This may explain the unusual thickness and lateral extent of the kaolin-rich layer at the Fei Tsui Road landslide.

Kaolin accumulations within discontinuities at both sites appear commonly to be associated with multiple minor movements, manifest in shearing along stress release and other relict discontinuities subparallel to the prevailing slope, and on rotations and tensional openings of subvertical joints. These enabled complex infillings of the discontinuities by alternations of kaolin, of varying compositions, and todorokite. As a kaolin-infilled discontinuity develops parallel to a slope, it will act increasingly as an aquiclude. This may promote yet further kaolin, derived from the weathered profile, to be deposited physically or chemically. Halloysite was the dominant clay mineral at, or close to, the surfaces of rupture and its development appears to have been favoured by shearing, at the expense of kaolinite.

Development of stress release joints subparallel to the slope could have been promoted by previous natural slope failures. Hence certain parts of slopes may undergo recurrent, i.e. cyclic failure, as appears to have been the case in parts of the study areas (Campbell & Koor 1996; Franks *et al*. 1997), and especially so in relation to coastal erosion of the toes of slopes.

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