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Editors Note:

This issue includes a new column "Comment and Reply", which introduces discussion of past articles published in the Hong Kong Geologist. The Classic Geology Series will resume in the next issue.

New High Precision U–Pb Zircon Ages for Mesozoic Intrusive Rocks from the Southern Hong Kong SAR

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Abstract

Four new high precision U–Pb single crystal zircon ages are reported from Middle Jurassic and Early Cretaceous intrusive rocks from southern parts of the Hong Kong SAR. An age of 151.9 ± 0.2 Ma has been obtained from a NE-trending rhyolite dyke (Hok Tsui Rhyolite) in SE Hong Kong Island. This is the first middle Late Jurassic age to be reported from Hong Kong and confirms earlier indications from inheritance data that a thermal event occurred in the region about 152 million years ago. The South Lamma Granite, which forms the southern half of Lamma Island, has returned an age of 148.1 ± 0.2 Ma. These new late Jurassic ages lie between established episodes of volcanism and plutonism at 162 ± 3 Ma and 146.4 ± 0.2 Ma, indicating that magmatic activity in the Hong Kong SAR was more continuous than previously thought. Two outcrops of quartz monzonite from D'Aguilar Peninsula (D'Aguilar Quartz Monzonite) and eastern Lamma Island have returned identical ages of 140.6 ± 0.3 Ma respectively indicating that they belong to the final phase of volcanism and plutonism earlier reported at c. 140 Ma.

摘要

在香港特別行政區南部的侏羅紀中期及白堊紀初期侵入岩之中，新發現了四個經高度精確的鈾鉛法測定的單晶鋯時期。從港島東南部採集的東北伸展流紋岩（鶴咀流紋岩）樣本，亦測定出形成於 151.9 ± 0.2 百萬年前。這是香港首次發現侏羅紀中晚期的證據，同時亦證實了早前發現的有關在大約 1 億 5200 萬年前曾發生熱事件的遺傳資料。構成南丫島南部的南南丫花崗岩已有 148.1 ± 0.2 百萬年歷史。這些侏羅紀新晚期岩石，藏於 162 ± 3 百萬年至 146.4 ± 0.2 百萬年的火山作用及深成作用層之間，顯示出香港特別行政區的岩漿活動，比以往所構想的更為連貫。在鶴咀半島（鶴咀石英二長岩）及南丫島東部發現的兩處石英二長岩露頭，均測定出有 140.6 ± 0.3 百萬年歷史，反映出兩者同形成於早前發現的約 140 百萬年前火山岩作用及深成作用的最後階段。

Introduction

Meticulous high precision U–Pb single crystal zircon dating of silicic volcanic and plutonic rocks in the Hong Kong Special Administrative Region (Hong Kong SAR) over the past five years (Davis et al., 1997; Campbell & Sewell, 1998) has revealed a comprehensive record of Mesozoic magmatic activity. These data have

also provided a foundation for calibrating other isotopic and age data from the region leading to an improved understanding of crustal evolution (Darbyshire & Sewell, 1997). This paper presents new U–Pb age data that add to the already comprehensive radiometric age database for the Hong Kong SAR.

Geological Setting

Jurassic to Cretaceous silicic volcanic rocks and related granitoid rocks crop out over approximately 85% of the land surface area of Hong Kong (1050 km²). They belong to a 400 km wide belt of Mesozoic (Yanshanian) magmatic rocks exposed along the coastal region of SE China and have been divided into four main volcanic groups and corresponding granitoid suites based on petrographic, geochemical and age criteria (Davis *et al.*, 1997; Campbell & Sewell, 1998; Sewell *et al.*, 2000). The spatial distribution and geometry of the volcanic centres and related plutons in Hong Kong are strongly controlled by NW-trending and ENE-trending faults. These faults are thought to have been active during a period of rapid crustal extension with associated strike-slip movement along the NE-trending Lianhuashan Fault Zone during the Late Mesozoic (Campbell & Sewell, 1997) (Fig. 1).

Sample sites

The analysed samples come from SE Hong Kong Island and Lamma Island (Fig. 2). Sample HK12066 was collected from a quartzphyric rhyolite dyke exposed at Hok Tsui (Hok Tsui Rhyolite) on the D'Aguilar Peninsula. The dyke is part of a swarm of NE-trending, strongly flow-banded light pink to white rhyolite dykes which intrude the Tai Po Granodiorite and Yim Tim Tsai Formation tuff at the southern tip of the peninsula. They are also exposed on the small offshore island of Kau Pei Chau.

Sample HK12075 was collected from granite exposed in the southern part of Lamma Island (South Lamma Granite), which has been extensively intruded by feldsparphyric rhyolite dykes. The South Lamma Granite is dominantly an equigranular medium-grained biotite monzogranite, with local fine-grained variants.

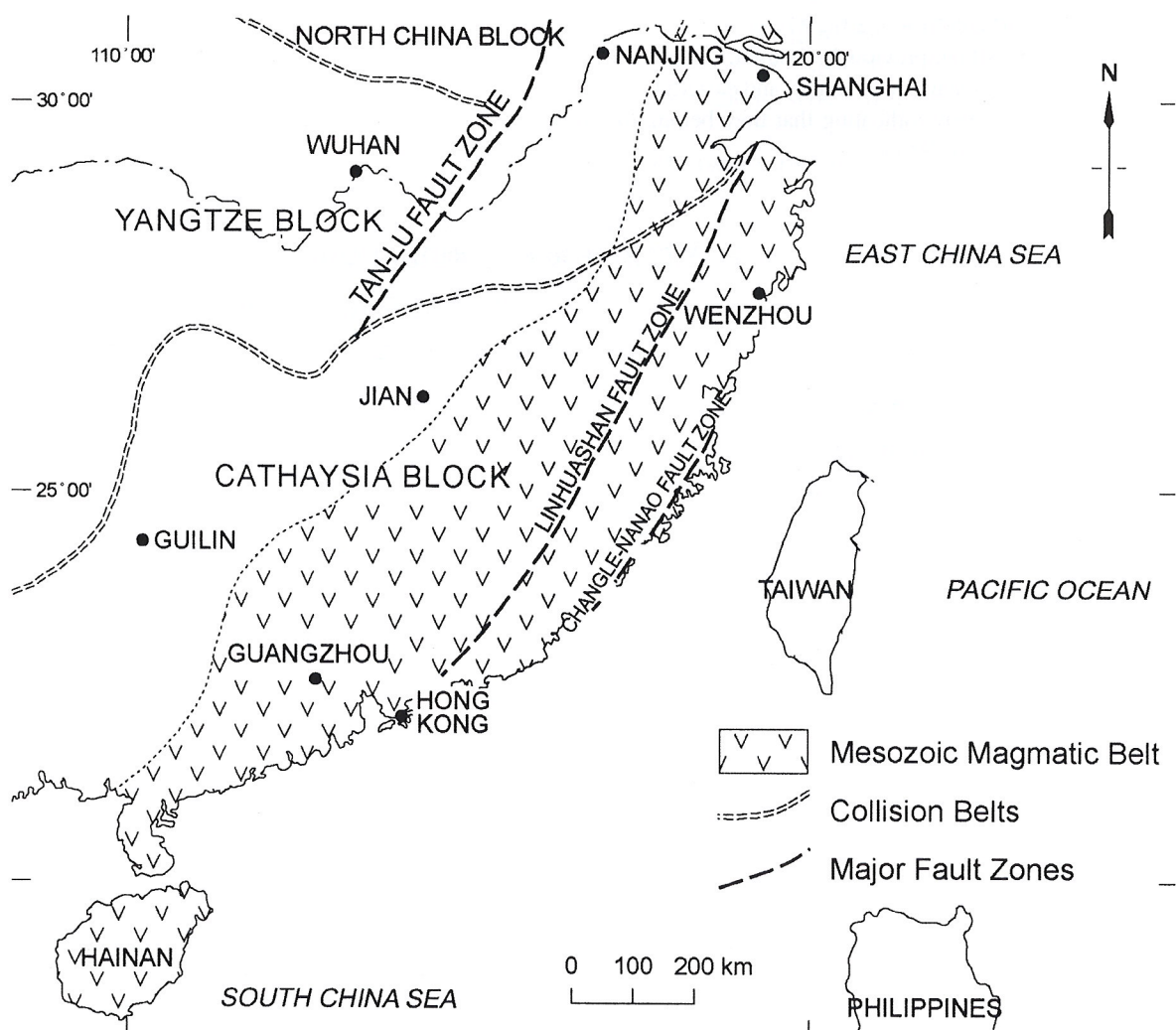


Fig. 1 Regional geological setting for Hong Kong rocks showing the distribution of Mesozoic igneous rocks and position of the Lianhuashan Fault Zone.

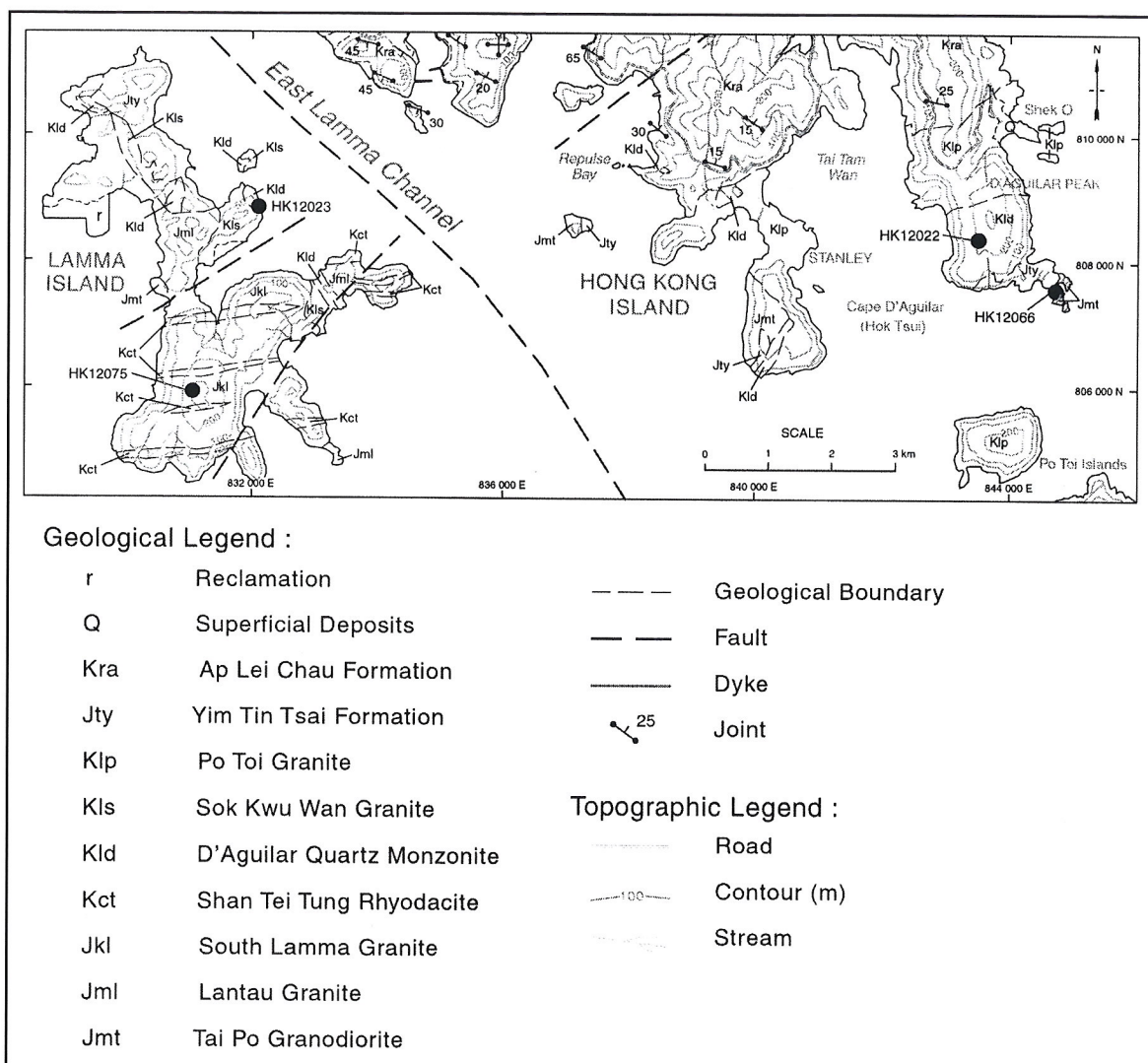


Fig. 2 Simplified geological map of southern Hong Kong showing the location of analysed samples, outcrop of relevant intrusive units, and major structural features (co-ordinates based on Hong Kong 1980 Grid).

Sample HK12022 was collected from a large outcrop of porphyritic fine- to medium-grained quartz monzonite on D'Aguilar Peninsula (D'Aguilar Quartz Monzonite). This intrusion has previously returned an Rb-Sr age of 147 ± 8 Ma (Sewell *et al.*, 1992).

Sample HK12023 was collected from an outcrop of quartz monzonite on the eastern side of Lamma Island in the vicinity of Lamma Quarry. The rock is fine- to medium-grained, porphyritic, and is compositionally similar to that exposed on D'Aguilar Peninsula.

Analytical Methods

Sample crushing was with a jaw crusher followed by a disk mill. Samples were passed over a Wilfley table to concentrate heavy minerals. Further heavy mineral separation was carried out by density separations with bromoform and methylene iodide and paramagnetic separations with a Frantz separator. Final

sample selection was by hand picking under a microscope. Exterior surfaces of selected zircon grains were removed by air abrasion (Krogh, 1982). Weights of mineral fractions were estimated by eye, a process that is found to be usually accurate to about $\pm 50\%$. This affects only U concentrations, not age information, which depends on isotopic ratio measurements (Table 1).

Zircon was dissolved using HF in teflon bombs at 200°C , after being washed in HNO_3 . ^{205}Pb - ^{235}U spike was added to the dissolution capsules during sample loading. Purification of Pb and U was carried out in HCl using 0.05 ml anion exchange columns (Krogh, 1973).

Pb and U were loaded together on Re filaments using silica gel and analyzed with a VG354 mass spectrometer in single collector mode. All of the measurements were made using a Daly collector. The mass discrimination correction for this detector has

Table 1: U-Pb isotopic data for zircon in rocks from the Hong Kong Region

No.	Fraction	Weight (mg)	U (ppm)	Th/U	Pb/Com (pg)	206/204	206/238	207/235	206/238 Age (Ma)	2 sigma	207/235 Age (Ma)	2 sigma	207/206 Age (Ma)	2 sigma	% Disc.
HK12066															
Hok Tsui Rhyolite															
1	5 Ab zr, crk	0.010	362	0.65	0.7	8338	0.02385	0.16166	151.95	0.35	152.16	0.53	155.4	7.2	2.2
2	4 Ab zr, spr, crk	0.015	341	0.64	1.7	4741	0.02385	0.16154	151.93	0.36	152.05	0.56	153.9	8.2	1.3
3	12 Ab zr, spr	0.020	262	0.68	1.0	8123	0.02383	0.16090	151.80	0.47	151.49	0.57	146.7	6.6	-3.5
HK12075															
South Lamma Granite															
4	4 Ab zr, incl	0.020	140	0.68	1.1	3821	0.02325	0.15718	148.17	0.40	148.23	0.76	149.2	11.9	0.7
5	1 Ab zr, melt incl	0.020	95	0.77	1.9	1484	0.02324	0.15648	148.08	0.33	147.62	1.34	140.3	22.3	-5.6
6	2 Ab zr, incl	0.020	231	0.68	2.3	2992	0.02322	0.15690	147.96	0.34	147.98	0.78	148.4	12.3	0.3
HK12022															
D'Aguilar Quartz Monzonite															
7	3 Ab zr, incl	0.015	100	n.m.	1.5	1480	0.02202	0.1474	140.44	0.21	139.58	0.70	125.0	12.3	-12.5
8	1 Ab zr	0.006	40	0.82	2.6	149.9	0.02205	0.1497	140.61	0.66	141.66	7.08	159.3	127.2	11.9
9	1 Ab zr	0.025	47	0.74	1.6	1050	0.02209	0.1487	140.86	0.24	140.74	0.97	138.8	17.0	-1.5
10	1 Ab zr	0.004	104	0.81	13.7	61.47	0.02224	0.1538	141.81	1.22	145.23	19.79	201.3	206.6	29.9
HK12023															
Quartz Monzonite - Lamma Quarry															
11	1 Ab zr	0.003	152	0.67	1.9	360	0.02202	0.1487	140.42	0.31	140.79	2.83	147.1	50.2	4.6
12	1 Ab zr, elong	0.008	67	0.67	1.1	699	0.02203	0.1469	140.46	0.26	139.18	1.55	117.5	27.7	-19.7
13	2 Ab zr, incl	0.008	142	0.56	0.7	2378	0.02207	0.1473	140.69	0.22	139.51	0.58	119.5	10.0	-17.9
14	1 Ab zr	0.003	245	0.50	3.9	283	0.02210	0.1497	140.88	0.34	141.67	3.33	154.9	59.4	9.2

Weights are based on visual estimates

Abbreviations: Ab - abraded; zr - zircon grain; crk - cracked; incl - inclusions, spr - short prismatic; elong - elongate, n.m. - not measured
Th/U calculated from radiogenic $^{208}\text{Pb}/^{206}\text{Pb}$ ratio and $^{207}\text{Pb}/^{206}\text{Pb}$ age assuming concordance.%Disc - per cent discordance for the given $^{207}\text{Pb}/^{206}\text{Pb}$ age

Pbcom is total measured common Pb assuming all common Pb has the isotopic composition of laboratory blank:

 $^{206}\text{Pb}/^{204}\text{Pb} - 18.221$; $^{207}\text{Pb}/^{204}\text{Pb} - 15.612$; $^{208}\text{Pb}/^{204}\text{Pb} - 39.360$. $^{206}\text{Pb}/^{204}\text{Pb}$ are measured values corrected for fractionation and spike. $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ratios are corrected for common Pb assuming laboratory blank composition. $^{206}\text{Pb}/^{238}\text{U}$ age, $^{207}\text{Pb}/^{235}\text{U}$ age and $^{207}\text{Pb}/^{206}\text{Pb}$ age are corrected for ^{230}Th disequilibrium assuming a magmatic Th/U of 4.2.

U decay constants are from Jaffey et al. (1971).

2 sigma errors represent uncertainties in the last significant digits.

been monitored for several years and found to be constant at 0.4%/AMU. Thermal mass discrimination corrections are 0.10%/AMU.

Because of depletion of the shorter half-life ^{235}U isotope, there is much less ^{207}Pb than ^{206}Pb for relatively young samples. For Mesozoic and younger samples, $^{206}\text{Pb}/^{238}\text{U}$ ages are much more precise and reliable than $^{207}\text{Pb}/^{235}\text{U}$ ages, and $^{207}\text{Pb}/^{206}\text{Pb}$ dates are quite imprecise because the concordia curve is nearly parallel to a line through the origin. Therefore, ages for these samples are calculated as $^{206}\text{Pb}/^{238}\text{U}$ ages. $^{206}\text{Pb}/^{238}\text{U}$ ages are sensitive to secondary Pb loss, but this is likely to have been eliminated by the abrasion treatment, at least for low-U zircons (limited radiation damage).

To minimise the possibility of inheritance, a minimum number of zircons were analysed in a fraction and zircons having characteristics typical of the igneous population, such as a euhedral shape and an abundance of melt or rod-like inclusions, were chosen for analysis. Inclusions may account for high common Pb values in some of the samples. Even fairly substantial amounts of common Pb (10's of picograms) have only a small effect on the $^{206}\text{Pb}/^{238}\text{U}$ age precision. Common Pb corrections below 10 pg are made assuming an isotopic composition similar to laboratory blank. Excess common Pb is corrected using the Stacey and Kramers (1975) value, which represents a crustal average. Concordia co-ordinates and ages in Table 1 are corrected for fractionation, blank and spike. $^{206}\text{Pb}/^{204}\text{Pb}$ values are corrected for fractionation and spike.

The plotted data (Figs. 3–6), as well as the ages in Table 1, are corrected for ^{230}Th disequilibrium, assuming a Th/U ratio in the magma of 4.2, the terrestrial average. This increases the $^{206}\text{Pb}/^{238}\text{U}$ ages by about 0.09 Ma in all of the samples. The concordia co-ordinates in Table 1 are quoted as measured values, uncorrected for assumed disequilibrium. Th/U is calculated from the measured $^{208}\text{Pb}/^{206}\text{Pb}$ ratio and $^{207}\text{Pb}/^{206}\text{Pb}$ age.

Ages, errors and probabilities of fit are calculated from the Davis (1982) program, modified for fitting $^{206}\text{Pb}/^{238}\text{U}$ data. U decay constants are from Jaffey *et al.* (1971). Probability of fit is a measure of the likelihood that data points overlap within error. In a random distribution of coeval data with correctly assigned errors, this would be expected to be 50% on average. Values below 10% are generally considered to indicate non-coeval or disturbed data.

Results

All samples yielded zircon in varying abundance. Crack-free zircons without evidence of cores or alteration were selected for abrasion. Averaged age errors are quoted at the 95% confidence level in the text. Error ellipses in Figs. 3 to 6, as well as errors in Table 1, are given as 2σ .

1. HK12066. Quartzphyric rhyolite dyke at Hok Tsui (Cape D'Aguilar), D'Aguilar Peninsula (844900E, 806580N; Fig. 2)

Zircon was moderately abundant in this sample. It consists of colourless short-prismatic grains, many with well-developed high-order crystal faces. Most of the zircons are cracked and have abundant amorphous melt inclusions. Three multigrain fractions gave concordia overlapping data that define an average age of 151.9 ± 0.2 Ma with an 87% probability of fit (Fig. 3). This is considered to date the crystallisation of the rhyolite.

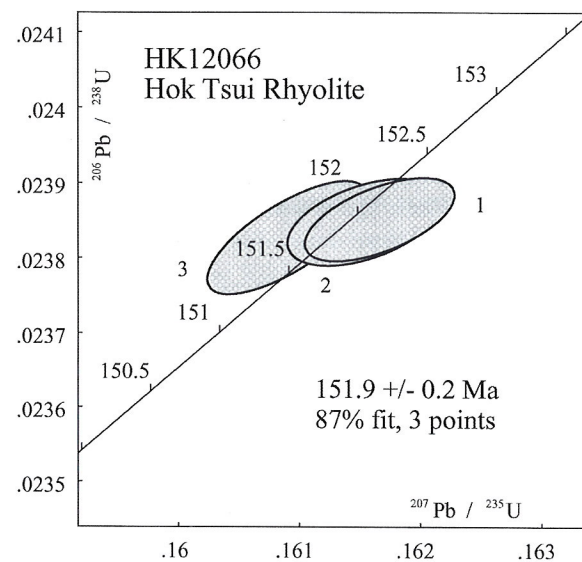


Fig 3 Concordia plot showing U–Pb isotopic data for zircons from HK12066, the rhyolite dyke at Hok Tsui (Cape D'Aguilar).

2. HK12075. Granite from the southern part of Lamma Island (831100E, 805800N; Fig. 2).

This sample yielded abundant but highly altered zircon. The population comprises colourless short and long prismatic crystals with well-developed high-order faces. Data from three fractions are concordant and define an average age of 148.1 ± 0.2 Ma with a 72% probability of fit (Fig. 4). This is considered to date emplacement of the granite

3. HK12022. Quartz monzonite from D'Aguilar Peninsula (843550E, 808150N; Fig. 2)

This sample produced abundant zircon as very fresh, euhedral, prismatic grains, many with high order crystal faces. Large amorphous melt inclusions are common in these grains. Four fractions produced concordant data that agree within error (44% probability of fit) and define an average age of 140.6 ± 0.3 Ma (Fig. 5). Two of the data are much less precise because of the small amount of Pb contained in the analyses and, in one case, an unusually high amount of common Pb. The close agreement over such a

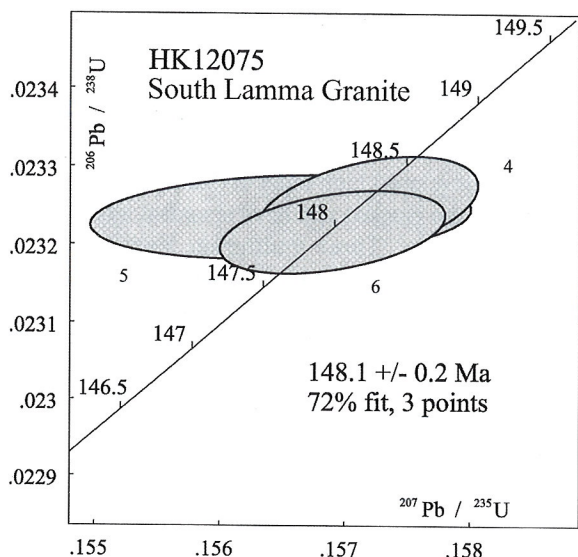


Fig. 4 Concordia plot showing U-Pb isotopic data for zircons from HK12075, the South Lamma Granite.

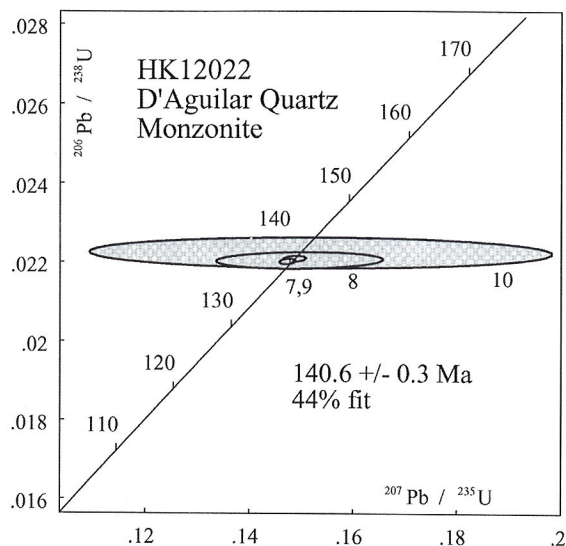


Fig. 5 Concordia plot showing U-Pb isotopic data for zircons from HK12022, the D'Aguilar Quartz Monzonite on D'Aguilar Peninsula.

wide range of radiogenic to common Pb ratios demonstrates that sources of systematic error, such as incorrect common Pb isotopic compositions, are probably minimal.

4. HK12023. Quartz monzonite from Lamma Island (831850E, 808610N; Fig. 2).

A small amount of very fresh, euhedral colourless zircon was recovered from this sample. The grains were morphologically similar to HK12022. Four concordant data points overlap and define an average age of 140.6 ± 0.3 Ma with a 67% probability of fit (Fig. 6). This is considered to be the best estimate for the age of the quartz monzonite.

Discussion

Previous U-Pb age-dating studies in the Hong Kong SAR have recognised four distinct periods of Mid-Jurassic to Lower Cretaceous magmatism at about 162 ± 3 Ma, 146.4 ± 0.2 Ma, 142.7 ± 0.2 Ma and 140.7 ± 0.3 Ma (Davis *et al.*, 1997; Sewell *et al.*, 2000). Campbell & Sewell (1998) argued that the crystallisation ages for most of the major volcanic and intrusive units in the Hong Kong SAR fall into one of these four main age categories. Previously, the only indication of magmatic activity outside of these distinct episodes was from zircon inheritance (Davis *et al.* 1997). These generally indicated Precambrian sources. However, rocks dated as belonging to the 146 Ma episode have consistently revealed inherited zircon ages of between 149.5 ± 0.4 Ma and 153.8 ± 0.4 Ma (Davis *et al.* 1997), suggesting that a latent igneous event may have occurred at around 151 ± 2 Ma. The new date from a rhyolite dyke at the southern tip of D'Aguilar Peninsula appears to confirm the presence of this thermal event. Furthermore, the location of the dyke,

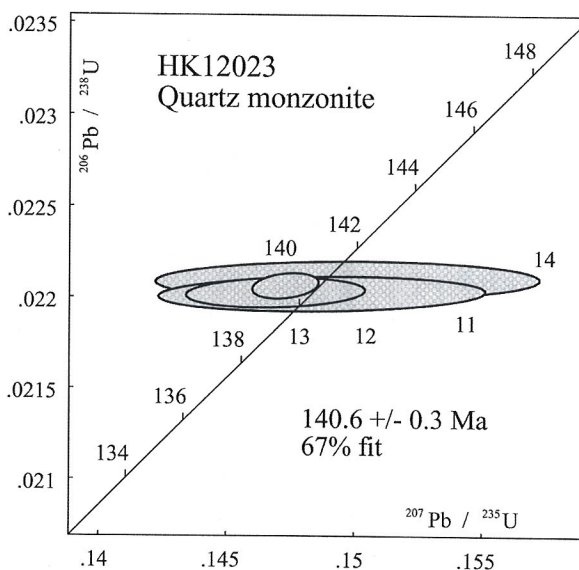


Fig. 6 Concordia plot showing U-Pb isotopic data for zircons from HK12023, the quartz monzonite on Lamma Island.

close to the southern margin of the Hong Kong SAR, suggests that a new magmatic age province may lie immediately to the south of Hong Kong waters.

The age of the South Lamma Granite is slightly older than the oldest age so far recognised for the c.146 million year old magmatic episode. The stratigraphically lowermost volcanic rocks belonging to the Lantau Volcanic Group on Lantau Island have been dated at 147.5 ± 0.2 Ma Campbell *et al.* (in prep), whereas the bulk of the volcanic and intrusive rocks within the Group and coeval Kwai Chung Suite have been dated at 146.4 ± 0.2 Ma (Davis *et al.*, 1997). The South Lamma Granite is cut by a swarm of E-W-trending rhyodacite dykes. These dykes

may signal the onset of rapid extension that characterised the main c.146 million year old magmatic episode (see Campbell *et al.*, 1998). Geochemically, the South Lamma Granite is similar to granites belonging to the Kwai Chung Suite, although prior to obtaining the new age it was assigned to the Cheung Chau Suite largely on the basis of petrographic criteria. Thus, the best interpretation for the South Lamma Granite is that it belongs to an early phase of emplacement of the Kwai Chung Suite.

The identical 140.6 ± 0.3 Ma ages of quartz monzonite from D'Aguilar Peninsula and Lamma Island indicate that they belong to the youngest period of volcanic and plutonic activity in the Hong Kong SAR, which was previously dated at 140.8 Ma (Davis *et al.*, 1997). Geochemical and petrographic similarities also suggest that these separate outcrops belong to the same intrusive unit (D'Aguilar Quartz Monzonite). Outcrops of quartz monzonite in Hong Kong are generally related to 'fissure-type' plutonic-volcanic assemblages (Sewell & Campbell, 1997) that are thought to mark deep crustal fractures and caldera boundaries. The linear series of discontinuous quartz monzonite stocks across southern Hong Kong Island and Lamma Island forming the D'Aguilar Quartz Monzonite may therefore mark a major structural boundary.

Conclusions

Four new precise U–Pb single zircon ages for intrusive rocks from southern Hong Kong lead to the following conclusions:

1) A magmatic event in the Hong Kong region occurred 152 million years ago. Although only one absolute zircon age for this event has been recorded, several previously dated samples from Hong Kong have revealed inheritance data from the same event.

2) The main magmatic episode at 146.4 ± 0.2 Ma was preceded by a precursory pulse at 148 Ma which may have signalled the onset of accelerated extensional tectonics. The new age for the South Lamma Granite also suggests that the E–W-trending rhyodacite dykes on Lamma Island belong to an early pulse of the Lantau Dyke Swarm.

3) Stocks of quartz monzonite in southern Hong Kong between D'Aguilar Peninsula and Lamma Island probably belong to the same intrusive unit. These stocks may mark the position of a major structural feature, possibly a caldera boundary or deep fault.

The new age data presented in this study indicate that Jurassic to Cretaceous magmatism in the Hong Kong SAR was more continuous than previously thought.

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Factors Affecting the Spatial Distribution of Landslides on Lantau Island – A Statistical Approach

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Abstract

The spatial distribution of landslides on Lantau Island (Hong Kong) for the year 1995 have been investigated using a descriptive statistic – the Location Quotient. Four landslide-governing factors were considered including: (1)geology, (2)slope gradient, (3)vegetation, and (4)annual rainfall. The method was found to be useful for testing the correlation between landslide distribution and each of the independent factors, and can serve as an alternative method to the commonly-used landslide density approach, particularly where areal data are not available. This location analysis has revealed that the landslide distribution of Lantau Island is highly correlated with its geology, slope gradient and annual rainfall, with vegetation (woodland) being relatively insignificant. These results are similar to findings reported in other comparable studies.

摘要

一九九五年香港大嶼山山泥傾瀉的空間分佈已被描述統計學 - 區位商數所分析。其包括四個有關的主導因素：(一)地質、(二)坡度、(三)植被、以及(四)年雨量。這方法被發現可測試山泥傾瀉分佈與其個別自變因素之間的相互關係，並可以作為另一種方法替代常用的山泥傾瀉密度分析，尤其當欠缺面積數據。這區位分析反映出大嶼山山泥傾瀉分佈與其地質、坡度及年雨量有相對較大的相互關係，但與植被(林地)的關係則相對地不明顯。這研究結果與其他可比較之研究相類似。

Introduction

Landsliding is the most common known type of mass movement that affects hillslopes in Hong Kong. Over the past 30 years, landslides in Hong Kong have been widely studied (Lumb, 1975; So, 1978b; Brand, 1985, 1989). However, earlier research mainly focused on particular landslide sites only and landslides were examined as case studies at a small-scale. Landslide investigations and records tended to be limited to the slope failures that had affected human settlements or urban areas. It was not until the initiation of the Natural Terrain Landslide Study by the Geotechnical Engineering Office in 1995 (King, 1999), that the spatial distribution of landslides on natural hillslopes was given attention. This change was mainly due to an accelerating rate of urban development adjacent to these previously undeveloped terrain (Evans, 1998;

Evans *et al.*, 1999; King, 1999). Since then, a number of studies have been carried out on natural slope stability problems, particularly on Lantau Island (Wong *et al.*, 1997; Franks, 1998, 1999; Wong & Lam, 1998; Fuchu *et al.*, 1999). The main statistical method used to determine the correlation between landslide propensity and natural terrain attributes (Franks, 1998, 1999; Wong *et al.*, 1998; Wong & Lam, 1998; Evans *et al.*, 1999; Fuchu *et al.*, 1999) has been through calculation of the landslide density (number of landslides per unit square kilometre) (Wong *et al.*, 1998; Wong & Lam, 1998; Evans *et al.*, 1999; Fuchu *et al.*, 1999). However, the method may not be applicable for those variable attributes that are without available updated numerical areal information, such as for vegetation or annual rainfall coverage (Ng, 2000).

This paper, therefore, attempts to offer an alternative statistical strategy, the Location Quotient, to analyse the spatial distribution of landslides on Lantau Island. This method is most widely used in economic geography and location analysis (Burt & Barber, 1996), but not in physical geography. It aims to find out a comparable degree of relationships among the relatively non-variable (geology and slope gradient) and variable (annual rainfall and vegetation) potential landslide-governing factors that contribute to spatial landslide distribution patterns. The applicability of this method is tested against comparable previous studies.

Research area and methodology

The study area, Lantau Island, lies in south western Hong Kong and with a total area of 143.82 km² (Lands Department, 2000) is the largest island in the SAR. Most of the terrain is mountainous with steep slopes, dominated by east-northeast trending ridges. The highest relief occurs in the central part of Lantau, where the second and third highest peaks of Hong Kong – Fung Wong Shan (Lantau Peak, 934 metres) and Tai Tung Shan (Sunset Peak, 869 metres) are located. Lowlands are limited and mainly confined to the coastline, which is indented by narrow deep bays (Langford, 1995).

The study involved aerial photograph interpretation, landslide mapping, ground-truthing, and the application of statistical methods, with the aim of determining correlations between the spatial landslide distribution and each of the potential landslide-governing factors.

A total of 46 vertical aerial photographs, dated November 23, 1995 (Survey & Mapping Office, 1995), were used to identify landslide locations over the island (Table 1). These cover the whole of Lantau and were taken from 10,000 feet.

Landslide locations identified from the aerial photographs were then mapped on a transparency laid on a 1:25,000 scale Lantau Island topographic map (the base map) (Survey & Mapping Office, 1996). Overlapping of this landslide distribution transparency with geology (Geotechnical Engineering Office, 1991, 1994, 1995a & b), slope gradient (Geotechnical Control Office, 1988a & b), annual rainfall (Hong Kong Royal Observatory, 1995) and vegetation maps (Survey & Mapping Office, 1996) was carried out in order to facilitate statistical analysis. It should be noted that these original maps were used after simplification and re-scaling procedures to enable comparison with the base map.

Quantification and statistical methods included determination of landslide density (number of landslides/km²), unit area measurement, and evaluating the Location Quotient (LQ). These were applied in order to find out the degree of correlation between the spatial landslide distribution patterns and the potential controlling factors.

To calculate landslide density, areal data for the specific factor(s) is needed. However, no available areal data has been found for vegetation (woodland) coverage or the annual rainfall ranges (2000-2200mm, 2200-2400mm, over 2400mm). Unit area measurement and LQ were used to provide the relative percentage of area coverage for each factor over the island. This is the ratio of the number of square units covered by the specific factor to the total number of square units of Lantau Island. Calculation of square units was carried out with the use of transparent graph paper. The Location Quotient (Burt & Barber, 1996) was crucial to this research. It was used as an index measuring concentration (which implies “density”) of landslides for each specific factor. This was done by calculating the ratio of the percentage of landslides occurring for a particular factor to the areal percentage of that factor over Lantau Island. This method enables comparison

Date of Aerial Photographs	Photograph Serial Number	Number of Photographs
23 November 1995	CN 12262-12264	3
	CN 12238-12242	5
	CN 12171-12179	9
	CN 12154-12168	15
	CN 12178-12188	11
	CN 12074-12076	3
	Total	46

Table 1 List of aerial photographs used

Location Quotient	Interpretation
LQ > 1	The distribution of landslides occurring for a particular factor (as a %) is greater than the areal distribution for that particular factor over Lantau Island (%) - indicates a relative high concentration (or higher density) of landslides over the areal base for that factor.
LQ = 1	The distribution of landslides occurring for a particular factor (as a %) is the same as the areal distribution for that particular factor over Lantau Island (%) - indicates an equal proportion of landslides over the areal base for that factor.
LQ < 1	The distribution of landslides occurring for a particular factor (as a %) is smaller than the areal distribution for that particular factor over Lantau Island (%) - indicates a relatively low concentration (or lower density) of landslides over the areal base for that factor.

Table 2 Interpretation of the location quotient (from Ng, 2000)

of landslide concentration for the four factors using the same base, even though two of the factors (vegetation and annual rainfall) lack numerical areal data. LQ considers the relative percentage rather than the absolute numerical value. The interpretation of LQ is summarized in Table 2. The change of LQ for attributes of a particular factor reflects the degree of relationship between landslide distribution and that factor.

Ground-truthing was also carried out in order to obtain first-hand information about the characteristics of landslides on Lantau Island with respect to specific geographical location.

Results

Characteristics of the spatial landslide distribution of Lantau Island

The spatial distribution of landslides on Lantau Island in 1995 was uneven (Fig. 1). In the northeast and eastern parts of the island, landslides were sparsely distributed. In contrast, a clustered distribution occurred in the central and western areas, where there was a greater number and higher density of landslides. High landslide density areas included: Ngong Ping, the hills to the east of Shek Pik Reservoir, the eastern part of Tung Chung, and the slopes to the west of Mui Wo (Fig. 1). It can also be noted that most landslides occurred in the interior mountainous part of the island, with very few occurring along the lowland coastline.

Aided by aerial photographs (Survey & Mapping Office, 1995), it was found that most landslides occurred on mid-slopes surrounding mountain peaks, forming a "circular" landslide pattern (Fig. 1).



Plate 1 Landslide scars located on upper valley slopes, with tongue zones pointing to the streamlines, Lantau Peak

At a smaller-scale, most landslide scars are found on the upper parts of valley slopes, a short distance below the crest of spurs (Plate 1). This spatial pattern has also been reported for other natural terrain landslide studies, with most landslides occurring on the upper valley-side slopes close to the watershed (Evans, 1998; Evans *et al.*, 1999; Franks, 1999).

Having noticed such distinctive landslide distributions over the island, this paper next attempts to explore some of the potential controlling factors including: geology, slope gradient, vegetation and annual rainfall.

Landslide distribution in relation to geology

The 1995 spatial distribution of landslides on Lantau Island varied with geology. On volcanic terrain, landslides occurred in clusters. In contrast, landslides on granitic hillslopes showed a sparse or dispersed distribution pattern. Very few landslides occurred on superficial deposits. No landslides formed on

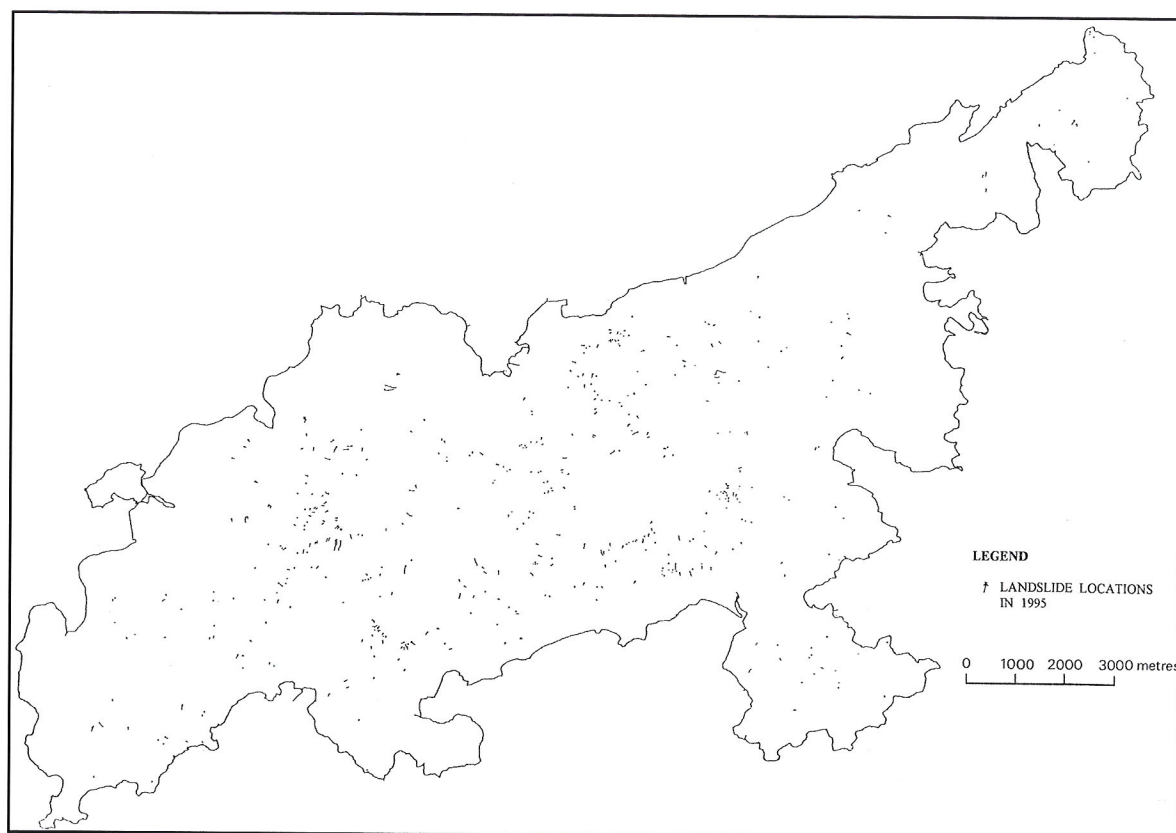


Fig. 1 Landslide location map for Lantau Island in 1995

sedimentary terrain. It is also interesting to note that most landslides were located near the "contact zone" between superficial deposits and volcanics (Ng, 2000, p.49).

Statistical results (Table 3) show that there are significant changes in Location Quotient in response to varying geology, especially when comparing volcanics with other rock types. Volcanic terrain has the highest number of landslides: 6.1 times more than on granites; 9.7 times more than on superficial deposits; and 3.7 times more than all other rock types combined. Landslide density (total number of landslides/km² for a specific rock type) is also highest on volcanics. The strong positive Location Quotient of 1.69 ($LQ > 1$), represents a very high concentration of landslides over volcanic terrain, while the low LQ values for other rock types reflect a sparse landslide distribution pattern. These contrasting LQ values with lithology suggest that geology is a significant controlling factor for landslide distribution.

Landslide distribution in relation to slope gradient

Landslides are unevenly distributed over different slope gradient ranges (Table 4). The data show an increase in the number of landslides as slope gradient increases from 0°-5° to 15°-30°, but then a slight decrease from 30° onwards. Though most landslides

(45.6%) occur on 15°-30° slopes, the highest landslide density (4.7 landslides/km²) is found for slope gradients of 30°-40°, where the LQ reaches its highest value of 1.40. Both values increase for slopes with gradients ranging from 0°-5° to 30°-40°, with a significant jump in these values at 15°-30°. The marked relationship between LQ and slope gradient indicates that slope angle is an important controlling factor for landslide distribution patterns. However, the influence of slope appears to be less significant at higher angles, where there is a minor decrease in LQ (Table 4).

Landslide distribution in relation to vegetation (woodland)

The spatial distribution of landslides shows little or no relationship (existence or non-existence) with that of woodland distribution (Ng, 2000) (Table 5). The statistical data actually show that the number of landslides occurring on non-woodland areas (mainly natural grass hillslopes, as noted on aerial photographs) is 5 times greater than that in wooded locations. However, this result is biased because of the small woodland cover over the island (Table 5). The Location Quotient helps to eliminate this problem and enables a real comparison. The LQ indicates that wooded locations have a slightly higher landslide concentration value ($LQ > 1$) of 1.09 than that of non-

Geology type	Geology areal extent		Landslide occurrence (Year 1995)		Landslide Density (no. of landslides/km ²)	Location Quotient (% of landslides/% of specified geology)
	Area (km ²) *	% of specified geology on Lantau	No of landslides	% of landslides on specified geology		
Volcanics	69.42	46.7	396	78.9	5.70	1.69
Granite	45.36	30.5	65	12.9	1.43	0.42
Sedimentary	1.23	0.8	0	0	0	0
Superficial deposits	32.54	21.9	41	8.2	1.26	0.37
Total	148.55	99.9	502	100		

Table 3 Landslide distribution on different rock types in 1995. *Source: Data combined and summarised from North Lantau (GCO 1988a) and South Lantau (GCO 1988b) GASP Reports

Slope gradient	Areal extent		Landslide occurrence (Year 1995)		Landslide Density (no. of landslides/km ²)	Location Quotient (% of landslides/% of specified slope gradient)
	Area (km ²) *	% of specified slope grad. on Lantau	No of landslides	% of landslides on specified slope grad.		
0°-5°	12.26	8.2	0	0	0	0
5°-15°	24.01	16.0	32	6.4	1.33	0.40
15°-30°	62.12	41.4	229	45.6	3.69	1.10
30°-40°	44.86	29.9	211	42.0	4.70	1.40
>40°	6.67	4.4	30	6.0	4.50	1.36
Total	149.92	99.9	502	100		

Table 4 Landslide distribution on different slope gradients in 1995. *Source: Data combined and summarised from North Lantau (GCO 1988a) and South Lantau (GCO 1988b) GASP Reports

Vegetation type	Areal extent		Landslide occurrence		Location Quotient
	Area (in sq. units)*	% over Lantau Island	No. of landslides	% of landslides	
Woodland	6165	14.8	81	16.1	1.09
Non-woodland	35623	85.2	421	83.9	0.98
Total	41788	100	502	100	

Table 5 Landslide distribution on woodland and non-woodland areas in 1995. *Source: Map work by counting the number of squares in terms of square units from transparent graph paper. Woodland is defined by the legend on the Lantau Island topographic map (Survey & Mapping Office, 1996)

Annual Rainfall (in mm)#	Areal extent		Landslide occurrence		Location Quotient
	Area (in sq. units)*	% of specified rainfall over Lantau Island	No. of landslides	% of landslides on specified rainfall	
2000-2200	10931	26.2	40	8.0	0.31
2200-2400	23682	56.7	298	59.4	1.05
>2400	7175	17.2	164	32.7	1.90
Total	41788	29.9	502	100.1	

Table 6 Landslide distribution for different annual rainfall range in 1995. *Source: Map work by counting the number of squares in terms of square units from transparent graph paper. #Source: Hong Kong Royal Observatory (1995)

woodland areas (LQ=0.98). This suggests that landslide occurrence has a slight tendency to concentrate on woodland areas. However, the LQ of woodland and non-woodland locations are both close to a value of 1, which demonstrates that landslide distribution on woodland and non-woodland areas is nearly in equal proportion (similar landslide concentration) to their areal extent. In summary, landslide distribution has an insignificant relationship with woodlands, thus the vegetation factor is inadequate to explain landslide distribution patterns on Lantau Island for the year 1995.

Landslide distribution in relation to annual rainfall

The distribution of landslides reveals a significant positive rainfall-landslide correlation. This is indicated by the increasing LQ as the annual rainfall of an area rises (Table 6). Therefore, locations with lower (or higher) amounts of rainfall correlate with lower (or higher) concentrations of landslides.

The highest number of landslides occur for the rainfall range between 2200-2400mm. However, the LQ of 1.05 suggests that the landslide distribution is in fact proportional to the areal rainfall pattern. The highest landslide concentration occurs in regions with the highest annual rainfall of over 2400mm (LQ=1.90). It is also noted that there is a significant change between areas experiencing 2000-2200mm (LQ=0.31) and 2200-2400mm (LQ=1.05). Such a marked response demonstrates that the annual rainfall exerts an important influence on the landslide distribution. It should also be noted that the rate of increase in LQ drops with further increasing annual rainfall (Table 6).

Discussion

The spatial distribution of landslides on Lantau Island, and especially the "circular" distribution patterns, are highly dependent on the form of mountain

ranges. Previous studies on the influence of hillslope form on landslide occurrence have been limited to a "micro"-scale (Fuchu *et al.*, 1999). Conflicting results have been presented by Wong & Lam (1998) based on the Geotechnical Area Studies Programme (GASP) of South Lantau (GEO, 1988b) and the site investigation carried out by Fuchu *et al.* (1999). The former study reported that there was a higher propensity for landslides to occur on concave sideslopes for gradients over 30° and for convex sideslopes of below 30° (Wong *et al.*, 1998). However, the latter study showed that hollows (defined as the "concave-out portion of hillslopes not occupied by channels", Reneau & Dietrich, 1987), were susceptible landslide locations. These conflicting observations probably reflect differences in study scale and difficulties encountered in determining the slope form.

The distribution of landslides close to the watershed may be related to oversteepening of slopes by active stream downcutting (Evans, 1998; Evans *et al.*, 1999), which would accord with Hansen's (1984) evolutionary model of Hong Kong's terrain. The distribution pattern may also imply a relationship with gully development (Zhang, personal communication). Despite the various suggestions, the position problem of landslides remains largely unsolved.

Geology

The results demonstrate that the landslide density data show contrasts between different lithologies, particularly for volcanic and granitic terrains. These data are largely consistent with previous studies (So, 1971, 1978a & b; Peng, 1986; Wong & Lam, 1998; Evans *et al.*, 1999), especially for the proportion of landslides on volcanic and granitic terrain (Wong *et al.*, 1998). This demonstrates the applicability of the Location Quotient for such studies.

Explanations for contrasts in landslide

concentration have included local geological/physical properties and the resulting soil behaviour of the weathered mantle (Lumb, 1962a, 1965; Ruxton, 1980; Irfan, 1996). However, these controls are not sufficiently adequate to explain the high concentration of landslides for areas underlain by the same lithology. This is especially true for volcanics near the "contact zone", despite the high LQ (1.69) (Table 3).

Further investigation of slope materials, instead of solid geology, may reveal fresh insights into such problems, given that landslides in Hong Kong mostly involve soil or unconsolidated materials. This is evident in a recent pilot study undertaken by Sewell & Fletcher (2000), which noted a close correlation between regolith and landslide distribution density.

Slope gradients

Data for the correlation between slope gradients and landslide distributions is similar to that from previous studies undertaken by the GCO (1988a), Wong & Lam (1998), and Wong *et al.* (1998). In general, the highest landslide frequency (in this study and others) occurs for the slope gradient range of 30°-40°, with landslide density and the Area Instability Index (AII) decreasing as slopes become gentler.

Steeper slope gradients are associated with more landslides because higher-angle slopes impose increased shearing stresses. The slope gradient range of 30°-40° has the highest landslide density. This is probably because these slope angles have exceeded the maximum frictional angle of decomposed volcanic and granitic materials, which are 30° and 35° respectively (Lumb, 1962a, 1965). However, the positive relationship between slope gradient and slope instability does not apply to slopes exceeding 40°, where a decreased Location Quotient is noted (Table 4). This lower landslide propensity for the steepest slopes may be due to the presence of stronger soil layers or less-weathered rock (Wong *et al.*, 1998). In addition, slope materials tend to be thinner on slopes >40°.

Woodlands

The relationship between vegetation and slope stability has been controversial. So (1971) reported that the highest frequency of landslides was associated with woodlands for a severe rainstorm in June 1966. He noted that 34.8% of the total number of landslides occurred in woodlands covering 8.4% of Hong Kong Island. However, Greenway *et al.* (1984) put forward an opposite view after a tree root study, and concluded that vegetation could improve slope stability. Similar findings have been reported by Fuchu *et al.* (1999), who found

that landslides mostly occur on barren or grass covered slopes, with few developing in forested areas.

The research reported here indicates that 16.1% of the total number of landslides on Lantau occurred in woodlands, which cover 14.8% of the island (LQ=1.09; Table 5), suggesting that landslides do not have a strong association with woodlands. This argues against the suggestions of So (1971), who's data indicate much higher LQ values of 4.14.

The woodland distribution patterns probably result from the combined positive and negative effects of vegetation on slope stability (Lee, 1985). The slight positive Location Quotient reported here for woodlands may be explained by considering the soil cover (Zhang, personal communication). Woodland areas indicate a thicker soil cover (needed to support tree growth), which may increase landslide potential by providing more unconsolidated slope materials. In contrast, non-woodland areas, such as grassland, may be relatively more stable because of thinner soils. Bare rock surfaces or bedrock outcrops, which are included in the "non-woodland" category, will also show lower LQ values for similar reasons.

Rainfall

The importance of rainfall in controlling landslides is supported by Wong (1997), who found a close relationship between the geographical distribution of rainfall and the distribution of the number of landslides for the year 1995. This is probably because rainwater can increase the shear stress by adding weight, and because increasing pore water pressure lowers slope stability (Plummer & McGeary, 1993; Selby, 1993; Montgomery, 1995).

However, such suggestions fail to explain the significant rise in LQ from 0.31 to 1.05 as rainfall increases to over 2200 mm per year, or to explain the decreasing rate of change in the LQ with increasing annual rainfall above 2400mm (Table 6). Instead, reference must be made to Lantau topography and geology in addition to the annual rainfall factors. Topography influences rainfall distribution while geology controls slope gradient and thus relief, which in turn could affect landslide distribution.

It should be noted that areas that experienced 2000-2200mm of rainfall in 1995 were mainly gentle and low-lying granitic terrains. These areas experienced a sparse landslide distribution (LQ=0.31). In contrast, significantly higher LQ values (1.05) were associated with areas of 2200-2400mm rainfall. These were higher and steeper volcanic terrains (Ng, 2000). The observed decrease in rate of change in LQ was associated with regions

receiving >2400mm annual rainfall. These were locations with the highest relief and the steepest slope gradients (>40°). Since the steepest gradient will not result in the highest landslide propensity (as has been discussed above), the rate of increase in LQ diminishes. Nevertheless, the LQ remains at its highest (1.90) for the various rainfall ranges (Table 6).

Conclusion

An alternative statistical approach has been proposed to analyse four potential controlling factors that influence the spatial distribution of landslides on Lantau Island. These factors include: geology, slope gradient, vegetation and annual rainfall. The data obtained by this method are comparable to those from other similar landslide studies. The approach yields more reliable data for variable factors, such as vegetation and annual rainfall. It also gives insights into controversial literature on the role of vegetation and slope stability.

The landslide distribution on Lantau Island during 1995 reflected geology, slope gradient and annual rainfall. Vegetation had a slight influence on distribution patterns. This has been determined from changing Location Quotient (LQ) values, which correspond with different attributes for a specific factor. Large changes in LQ values imply close relationships between landslide distribution and the particular factor being investigated.

The significance of this study is limited in part because statistical analysis for each factor have been carried out separately. Thus the landslide distribution has not been fully explained and some landslide location problems remain unsolved. However, the interrelationships among the various contributing factors have been noted and discussed.

The study has provided an empirical basis for further in-depth theoretical investigation. Based on the research results, it is noted that geomorphology has the potential to increase our understanding of landslide distribution patterns. As yet, a full explanatory theory has not been established to account for the spatial variation. Further research is needed to unravel the complex causal relations behind this geomorphological phenomenon.

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The Influence of Geological Structures on Natural Terrain Landslides

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Abstract

Many natural terrain landslides in Hong Kong commonly occur within structureless colluvial deposits. However, natural terrain failures also occur within saprolite. These failures, some of which are large in size, are often controlled by geological structures. This paper presents observations from two sites in Hong Kong where geological structure, in particular moderately inclined discontinuities, had a significant influence on the location and type of natural terrain landslides observed.

摘要

香港的天然山坡山泥傾瀉一般發生在無結構的坡積土地帶。不過，為數不少的崩塌事故亦在風化土層發生。這種崩塌事故一般受到地質構造的控制，所涉及的泥石體積通常相當大。本文載述對香港兩處地點的觀察所得，該兩處地質構造，尤其是中度傾側的斷裂帶對天然山坡山泥傾瀉發生的地點和類別有重大影響。

Introduction

Natural terrain failures commonly occur within the mantle of colluvium which covers the natural terrain of Hong Kong. Wong *et al.* (1998), reviewing natural terrain failures on Lantau Island resulting from Typhoon Ira in November 1993, noted that of the 56 landslides studied in detail, 84% occurred in "a thin layer of bouldery colluvium". However, from both reports in the literature and recent inspections of the natural terrain failures at two sites in Lantau and Tsing Shan, it is apparent that some of the natural terrain failures are structurally controlled to varying degrees. In addition, at both sites inspected there appears to be a strong spatial relationship between landslide source areas and proximity to rock outcrops. This paper reviews existing data from the investigations of natural terrain failures, presents observations from two recently examined sites and discusses the implications of these observations.

Structurally controlled natural terrain landslides in Hong Kong

Whilst there has been considerable discussion regarding the influence of geological structure on landslides, in particular large ($>50\text{m}^3$) landslides, in cut

slopes (e.g. Martin, 2000), their influence on natural terrain landslides should also deserve attention. The Geotechnical Engineering Office (GEO), and their consultants, have been systematically studying landslides in Hong Kong, including natural terrain failures (Wong & Ho, 2000). Table 1 summarises selected landslides that were identified as being controlled to varying degrees by geological structures. The influence of moderately inclined discontinuities sub-parallel to the local topography on these landslides is noteworthy.

Hencher (2000) described typical discontinuity types in Hong Kong. In particular, he noted that discontinuities sub-parallel to the local topography result in the concentration of weathering, the development of clay infills, and act as conduits for water flow. These moderately inclined discontinuities are sub-parallel to present or pre-existing topography. They are variously referred to as stress relief joints, unloading joints, sheeting joints, relief joints, release joints and exfoliation joints in the literature. They are typically found in granites, although they also occur in volcanic rocks, and are commonly considered to form due to a change in in-situ stress following the

Report No.	Location	Date	Volume(m ³)	Observations
LSR 4/98	Sha Tin	2.7.97	100	"heavily stained surfaces dipping between 45° and 55° were exposed locally in the base of the landslide scar, which were interpreted as sheeting joint surfaces"
LSR 11/98	Kwai Chung	8.5.97	800	"Fine to coarse grained granite with surfaces orientated generally downslope at 26 to 40°"
LSR 19/98	Ma On Shan	2-3.7.97	1300	planar scar formed by persistent planar discontinuity dipping sub-parallel to the slope at about 55° to the northwest. The discontinuity was coated with iron oxide, kaolin and traces of epidote and possibly talc which suggests that it may have been affected by hydrothermal alteration
LSR 7/99	Sai Kung	9.6.98	900	"complex local geological hydrogeological and geomorphological characteristics of the site probably played a significant role in the landslide although the precise contributions of these features to the failure are not certain"
LSR 14/99	Lok Keng Wong Uk	24.5.98	150	"the presence of adverse joint orientations in the source area indicates that relict jointing in the weathered rock mass probably contributed to the failure"
GEO,2000	Sham Tseng	23.8.99	480	joint set subject to toppling failure and this probably "disturbed and weakened the rockmass and adversely affected the local hydrogeology by promoting direct infiltration through open or partially infilled joints"

Table 1 Recent Structurally Controlled Natural Terrain Landslides. Note: LSR = Landslide Study Report issued by GEO

removal of the superincumbent load, usually by erosion. These joints are often lenticular in nature and Nichols (1980) noted that stress relief features are often curved, and commonly terminate at their intersection with tectonic joints.

However, other origins of moderately inclined joints are possible. Some may be of primary origin as similar features are found within igneous intrusions. Possible mechanisms for their formation are cooling at the apex of a flat lying intrusion, and fractures induced at the walls and roof of an intrusion by continued movement within its core (Price, 1966; Sewell *et al.*, 2000). Low angle joints may also be found in relation to thrust tectonics. In view of the uncertainty of the origin of these discontinuities, the term sheeting joint has been adopted in this paper. Regardless of the origin of these discontinuities, the importance of moderately inclined joints on the development of weak clay infills has been described by Parry *et al.* (2000), who concluded that the thickest clay infills within the weathered profile, tend to develop on these surfaces.

The appearance of these discontinuities can vary greatly in the field from barely visible surfaces with a thin film (<1mm) of clay infill within completely decomposed rock (Plate 1), to wide aperture joints within moderately to slightly decomposed rock with significant concentrations of groundwater resulting in alluvial type infills of medium to coarse sand (Plate 2).



Plate 1 Discontinuity with thin (<1mm) clay infill in Grade V granite



Plate 2 Discontinuity in Grade III granite, infilled with alluvial sand

Tsing Shan Range Landslides

On 14 April 2000 several natural terrain landslides occurred on the slopes of the Tsing Shan range above Leung King Estate, Tuen Mun (Plate 3). Of the four landslides inspected by the author, three (Landslides 1-3) had a degree of structural control. The area is located within the Tsing Shan Granite pluton that comprises fine- to medium-grained megacrystic granite (Sewell *et al.*, 2000). Landslide 1 was the largest of the four landslides inspected and had an estimated source volume of 150m³. The initial failure was considered to be a joint-controlled translational rock slide/debris flow of predominantly Grade III/IV granite, approximately 20m³ in volume. The surface of rupture was a sheeting joint dipping at 44°, steepening to 60° in the main scarp. Above the sheeting joint, the rock



Plate 3 Landslides on Tsing Shan Ridge. The four landslides inspected are those on the right side of the valley, Landslide 1 being nearest to the camera. Note the location of landslides with respect to rock outcrop.



Plate 4 Landslide 1, Tsing Shan. Basal release surface controlled by sheeting joint dipping 44-60°/166-198°. Note the preferential weathering along the joint surface and dilation of overlying rockmass.

mass was dilated with numerous clay infilled joints. (Plate 4). Following the initial landslide, a secondary failure occurred in the east flank, which occurred predominantly within colluvium

Landslide 2 comprised a translational debris flow of approximately 20m³ in volume located at the head of an ephemeral stream line. The scarp was joint-controlled with the failure predominantly within completely decomposed granite. The surface of rupture was a sheeting joint dipping at 50°.

Landslide 3 comprised a translational rock slide almost entirely composed of Grade III/IV rock with an estimated volume of 40m³. A sheeting joint formed the surface of rupture with a steep sub-vertical joint forming the main scarp. Fissure flow was evident from the joint at the base

Landslides 1 to 3 were all at, or close to, the toe of rock outcrop (Plate 3).

Shek Pik Landslides

Two natural terrain landslides occurred above a school and hostel at Tung Wan, Lantau in September 1999 (Plate 5). One landslide was channelised and deposited debris in a drainage channel within the site. The second was an open hillslope failure that deposited debris 6m from the crest of the cut slope adjacent to the site. The site

has recently been the subject of a natural terrain hazard assessment (Parry, 2001).

The 1:20 000-scale geological map (GEO, 1992), shows the study area to be underlain by rhyolite lava and tuff of the Lantau Formation, Repulse Bay Volcanic Group, with a northeast-southwest trending zone of metamorphism. Bedding is shown as dipping at 60° to the west on the foreshore and at 55° to south-east adjacent to South Lantau Road

The rock mass at the site has two sub-vertical orthogonal joint sets (a moderately widely spaced set at 80°/045° and a widely spaced set at 70°/315°) parallel and perpendicular to the major northeast-southwest trending fault beneath the nearby Shek Pik reservoir. In addition to these joint sets, which given their relationship to the fault are considered to have a tectonic origin, a sheeting joint set has locally developed sub-parallel to the natural terrain (45°/220°). The influence of these joint sets on natural terrain landsliding was evident in the recent landslides. Both landslides were structurally controlled to a large degree. The right flank release surface area of the channelised debris flow, with an estimated source volume of 120m³, formed by the northeast-southwest joint set and the basal surface at both landslides being formed by a southeast



Plate 5 Landslides at Shek Pik, Lantau, note vicinity of outcrop to source areas

dipping, sheeting joint set. No significant clay infills were observed in discontinuities exposed.

As at Tsing Shan the failures occurred within 15 m of the toe of rock outcrop.

Conclusions

At the two sites, one in granite the second in coarse ash crystal tuff, sheeting joints were an important structural control of natural terrain landslides. The landslides were initiated close to rock outcrops and dilation of the rock mass was evident. Aerial photograph interpretation suggests this relationship is more general, with relict failures of similar nature in similar locations. At Tsing Shan, preferential weathering along the sheeting-type joints was observed and on-going deterioration of the rock mass inferred.

Despite a wealth of available site specific discontinuity data, the regional development of joints in Hong Kong has (Sewell, *et al.*, 2000) received little attention to date. Importantly, the reasons for the local occurrence of sheeting joints are not known (Hencher, 2000). However, sheeting joints dipping parallel to the topography, especially

where located below areas of rock outcrop, are potential loci for initiation of natural terrain landslides that involve weathered rock. These joints may contain clay rich infill and may be overlain by a relatively open and more permeable rock mass. Their location at the toe of rock outcrops will tend to result in a large amount of run-off being directed into the open rock mass giving rise to the development of cleft water pressures and perched water tables. The identification of such areas, and assessment of their landslide susceptibility, should be one of the main areas of investigation in natural terrain hazard studies, particularly if these locations have a history of previous failures.

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Recognition of Structural Features in Sai Kung District, Eastern Hong Kong, Interpreted from a Shaded Relief Map

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Abstract

An area can be made to appear 3-dimensional on a plan using a shaded relief map, derived from Digital Elevation Model. If a high-resolution model is used, it is possible to distinguish a wide range of subtle geomorphic features. High-resolution shaded relief maps have considerable value in desk studies, aiding in preliminary interpretation of catchments and drainage patterns and in delineating structural features. Construction of a shaded relief model for Hong Kong is described and interpretation of the model is compared with that of aerial photographs and satellite imagery. This paper also presents an example of interpretation of structural features from a shaded relief map in the Sai Kung District, Eastern Hong Kong. Features identified include those that have been interpreted in earlier mapping and some previously unrecognised and uncertain features, including a major NNE-SSW trending topolineament in the northwest of the Sai Kung District extending from Hoi Ha Wan to Tai Wan.

摘要

在數碼立視模型所衍生出的立體地形圖的協助下，某地區的立體圖可展現在平面圖之上。一幅解像度高的立體地形圖，可幫助區分不同的地貌，這對於桌面研究非常有價值，例如在詮釋集水區和排水模式以及找出地形結構等方面。本文件透視了香港立體地形圖的製作過程，並概述根據立體地形圖詮釋位於港島東部的西貢區的地質結構情況。詮釋結果會與航空照片及衛星圖像的解譯作比較。在該立體地形圖上，我們可辨認出那些早已被驗證的地質結構，以及一些未經證實的地形線，其中包括位於西貢西北部的一條東北偏北至西南偏南向的大型地形線，從大河灣一直伸延至大灣。

Introduction

The structural geology of the Hong Kong SAR was summarised by Sewell *et al.* (2000) as part of a review of the geology of Hong Kong by the Hong Kong Geological Survey (HKGS) of the Geotechnical Engineering Office, Civil Engineering Department. A variety of data, including topographic survey data, mapping records, gravity models and marine magnetic survey results, were assessed.

The HKGS is now extending the interpretation of the major structures in Hong Kong with reference to the linear features

observable on a shaded relief map of the Hong Kong SAR. This shaded relief map was derived from a Digital Elevation Model and was included as one of the maps accompanying the recently published memoir of the Pre-Quaternary Geology of Hong Kong (Sewell *et al.* 2000). No detailed interpretation of the map has been carried out so far.

Some topolineaments, but not all, displayed on the shaded relief map are likely to be faults. Therefore, further confirmation of individual features is required in the field.

Digital Elevation Model

Surface topography is usually represented on topographic maps by contour lines. This method is good in terms of human perception but is not suitable for further processing by computer. To prepare computer visualisations of topography, it is necessary to first convert the data into a more appropriate data structure. The most commonly used structures are the Triangulated Irregular Network (TIN) model and the Digital Elevation Model (DEM). The TIN model uses input point and line data to form a network of triangular facets to represent the surface. In the DEM, the area is divided into a regular grid of square cells, and elevation value for each grid cell is interpolated from input data.

A range of elevation data was compiled to build the territory-wide model. A TIN Model was found to be more suitable for initial model development, due to the uneven distribution of source data. The main data used were the 10m contours and stream lines from the 161 LIC (Lands Information Centre of the Survey and Mapping Office, Lands Department, Hong Kong SAR Government) 1:5,000-scale maps and spot heights and a selection of vertices from the 2m contours from the 3,200 LIC 1:1,000-scale maps. In urban areas, where contour data are sparse, elevation information was provided from the ground level records of 60,000 drillhole logs. Contrasting surface morphology was maintained by using boundaries of alluvial deposits (HKGS 1:20,000-scale maps) and fill areas (HKGS 1:100,000-scale maps) as "hard breaklines". The TIN model was then converted into a DEM with a 5m grid. Validation of the DEM has shown that the Root Mean Square Error of the elevation is about 1.5m, though some errors and inconsistencies in the original data and artefacts from the various processes used inevitably remain.

Numerous computer algorithms are available to analyse DEM surface representations. These include derivation of slope, aspect, and surface runoff characteristics. A shaded relief map is a visual derivative of the DEM that helps users see a plan of the terrain three-dimensionally. The version discussed here combines a map of simulated shadows overlain by a semi-transparent coloured elevation map.

The DEM was created by Advanced Business Inc., under a Consultancy Agreement with the Civil Engineering Department, using Arc View 3.2 with 3D Analyst. The HKGS then produced the shaded relief map using Arc Info 8.0.

Shaded Relief Map

The shaded relief map for the Hong Kong SAR as shown in Fig. 1 is "lit" from a hypothetical sun position from the northwest with an elevation of 45°. Colours on "shaded" south and east facing slopes appear darker. Note that the small scale illustrations in this paper do not do full justice to the shaded relief map which is best viewed on screen at a scale of about 1:25,000. When viewed on a computer screen, the sun angle can be varied "interactively", enabling enhancement of features with different orientation and relief.

Linear features revealed on this map are referred to here as "topolineaments" since their construction is mainly based on the elevation data extracted from the LIC maps (discussed in previous section). These topolineaments may represent a variety of features, including natural drainage courses, structural features (e.g. faults and persistent joints), stratigraphic bedding, magmatic contacts (e.g. intrusive contacts between different rock bodies and dykes) or human modifications of the land. The nature of each of the topolineaments must therefore be verified by field checking.

The well-known dyke swarms in the northeast of Lantau Island appear as discrete lineaments trending ENE-WSW on the shaded relief map, while the terraced alluvium along the Lam Tsuen Valley to the west of Tai Po stands out clearly on the map.

Comparison of Shaded Relief Map with Aerial Photograph Interpretation (API)

The method for interpreting structures from topography on a shaded relief map is essentially the same as that used for interpreting topography on aerial photographs.

In viewing aerial photographs, consecutive photos should have a minimum overlap of 60%. Images on the aerial photographs are increasingly distorted away from the centre (principal point) of the photographs. In other words, the edges of the photographs are more distorted. However, the shaded relief map does not suffer from this limitation. Vertical exaggeration is another problem encountered in aerial photograph interpretation. By contrast, the shaded relief map can be produced to natural scale, or with vertical exaggeration as is required. Very often, obscurity, such as vegetation cover,

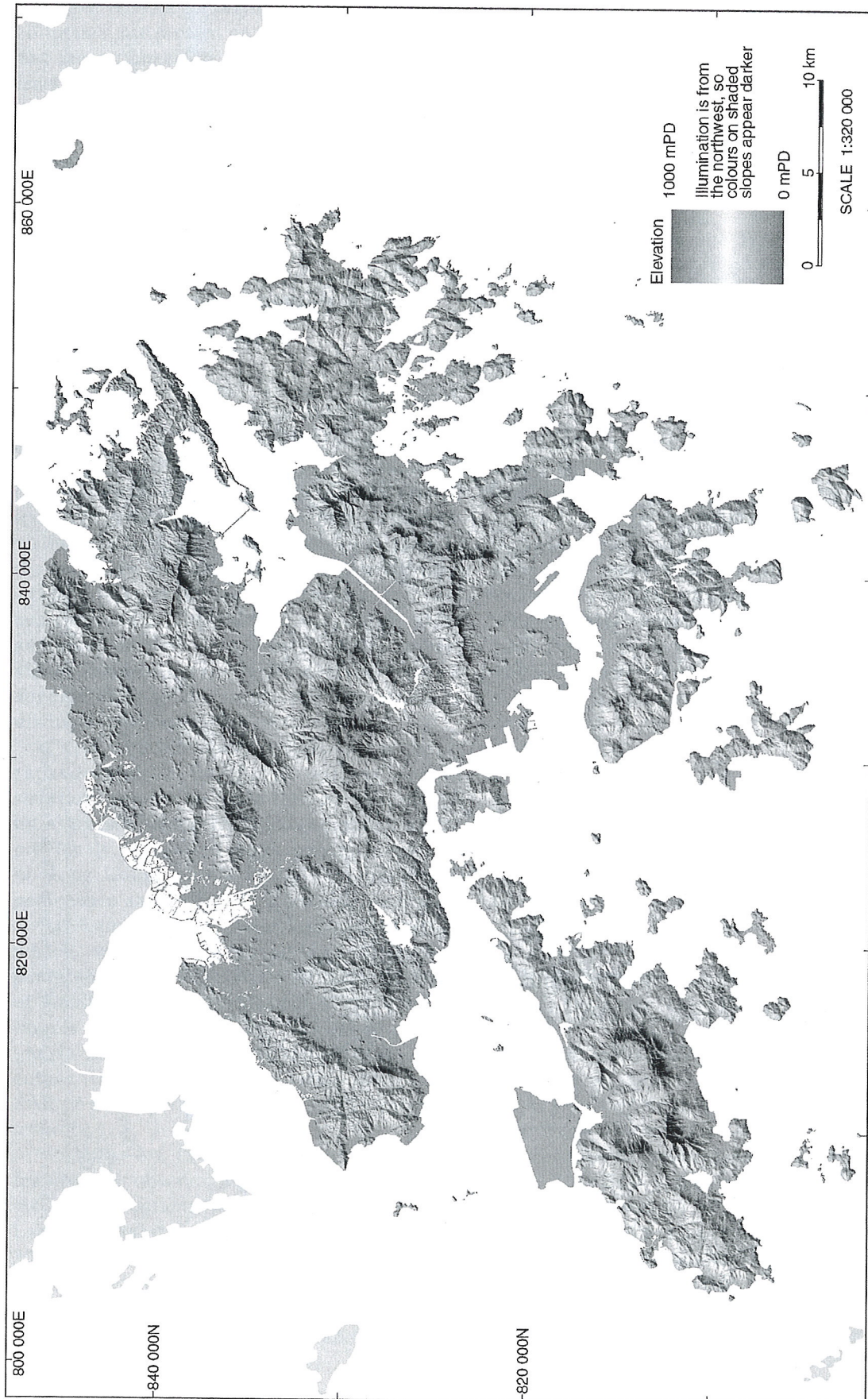


Fig. 1 Shaded Relief map of the Hong Kong SAR (original in colour)

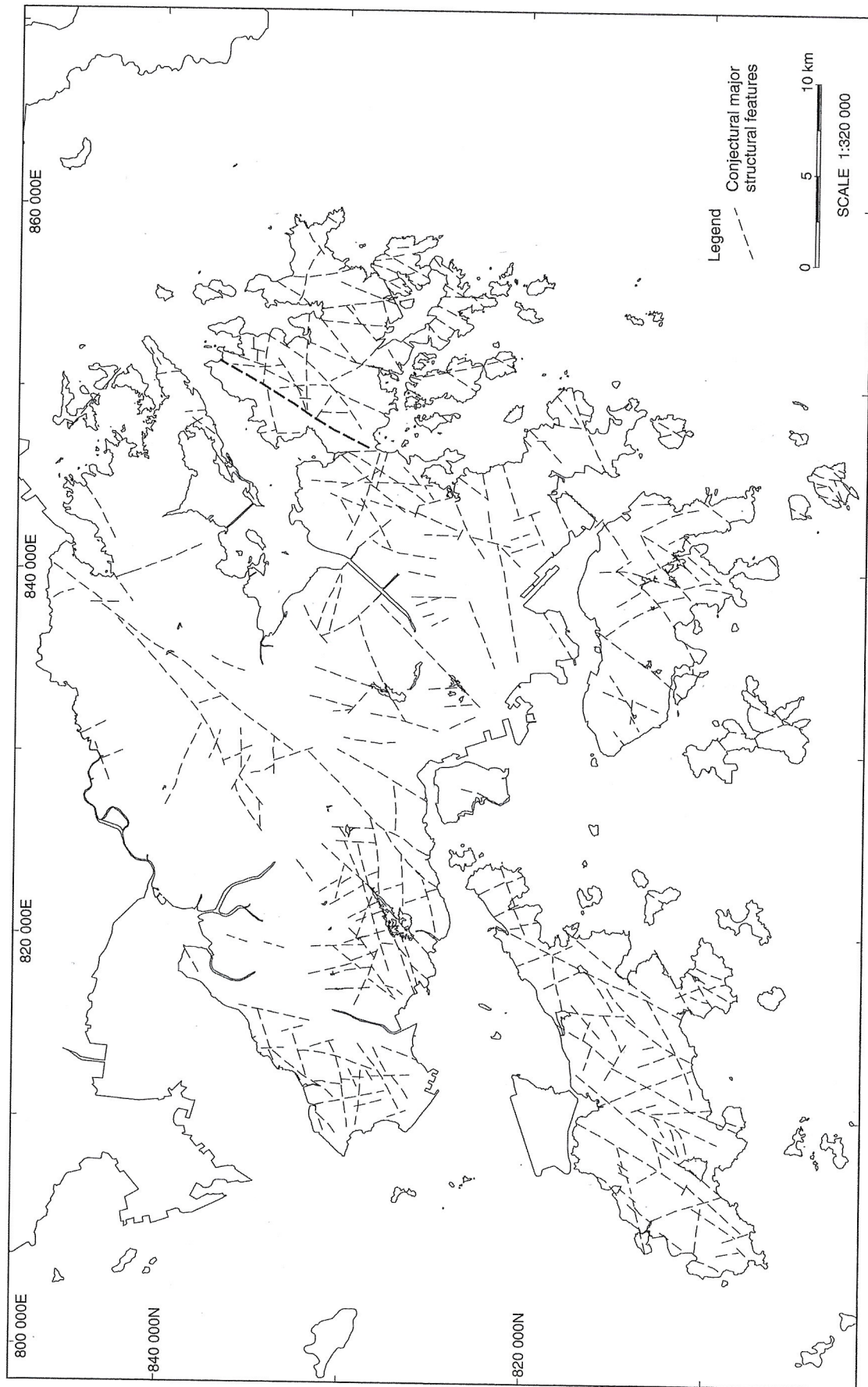


Fig. 2 Major structural features of the Hong Kong SAR (based on the shaded relief map)

cloud, mist/smog, shadow and atmospheric pollutants, are present on the aerial photographs and areas flanked by these obscurities are not readily interpreted as there is no way to eliminate the obscurities once the aerial photographs are taken. In creating a shaded relief map, only topography is considered. A shaded relief map thus gives a very "pure" view of topography without any natural or man-made factors to obscure the appearance.

Comparison of Shaded Relief Map with Satellite Images

Satellite images can be of grey tone, natural-colour or false-colour, depending on the goal of study, the properties of the features being captured and the bands (a range of electromagnetic wavelengths) chosen for the imagery. In false-colour images, parts of the non-visible spectrum are expressed as one or more of the red, green and blue components. In the most commonly seen false-colour images, the very near-infrared is displayed as red, red as green and green as blue. For instance, water absorbs all the incident energy in the near-infrared. It appears dark on the image and can easily be distinguished from other surfaces.

As with the shaded relief map, remotely sensed satellite images permit viewing of structures that are far larger than can be observed by a ground view. For instance, many of the previously recognised major structural features in Hong Kong, mainly faults with significant persistence and a NNE-SSW trending lineament at Sai Kung (formerly uncertain and details of which will be discussed in subsequent paragraphs), can be observed on the two mosaics of Landsat Thematic Mapper (TM) satellite images held by the HKGS. These two images, one in natural-colour and the other in false-colour (infrared), cover the entire Hong Kong SAR presenting a largely undistorted view of the territory.

Many of the natural and man-made features that obscure the aerial photographs also mask the topography in the satellite images. The Landsat imagery has a pixel resolution of about 30m, which is considerably lower than the 5m grid of the high-resolution shaded relief map. However, satellite images with resolution of 1-2m are now available for Hong Kong, though have not been reviewed for this paper.

Principle Structures of Hong Kong

Most of the faults in Hong Kong are sub-vertical or steeply inclined. They often produce negative topography. This is because the rocks are generally highly fractured within the fault zones, so enabling deeper penetration of surface runoff and resulting in deep weathering and enhanced erosion. Fig. 2 summarises the major topolineaments for the Hong Kong SAR as evident on the shaded relief map in Fig. 1.

Many of the most prominent topolineaments in Fig. 2 coincide with previously recognised faults (e.g. Lai & Langford, 1994) and those that have been published on the Hong Kong Geological Survey 1:20,000-scale and 1:100,000-scale geological maps. The NE-SW trending faults are generally aligned with the northeast-trending Lianhuashan Fault Zone and are associated with significant strike-slip movement (Sewell *et al.*, 2000). They are the most laterally persistent and widest faults in Hong Kong, and have the most significant impact on the topography of Hong Kong. NW-trending faults are generally shorter and less continuous and ENE (including E-trending) faults can also be identified. Similar trends for topolineaments are noted in Fig. 2. Some previously unrecognised or uncertain features, which may be faults, are also apparent.

Two shallowly inclined thrust faults are well documented in the northern parts of the Hong Kong SAR. However, they are not readily recognisable on the shaded relief map as they do not produce such obvious depressions in the topography as the steeply inclined faults.

Principle Structural Features in Sai Kung District, Eastern Hong Kong

The present study focuses in particular on the Sai Kung District, Eastern Hong Kong and the delineation of major structural features based entirely on the shaded relief map of the HKSAR. The location of the Sai Kung District within the Hong Kong SAR is shown in Fig. 3. Fig. 4 shows an enlarged portion of the shaded relief map covering the Sai Kung District.

Four major sets of topolineaments are evident on Fig. 4. They trend (i) E-W varying to ESE-WNW, (ii) NE-SW varying to NNE-SSW, (iii) NW-SE and (iv) N-S varying to NNW-SSE. Most of these topolineaments are interpreted as faults as they are consistent with previously established faults.

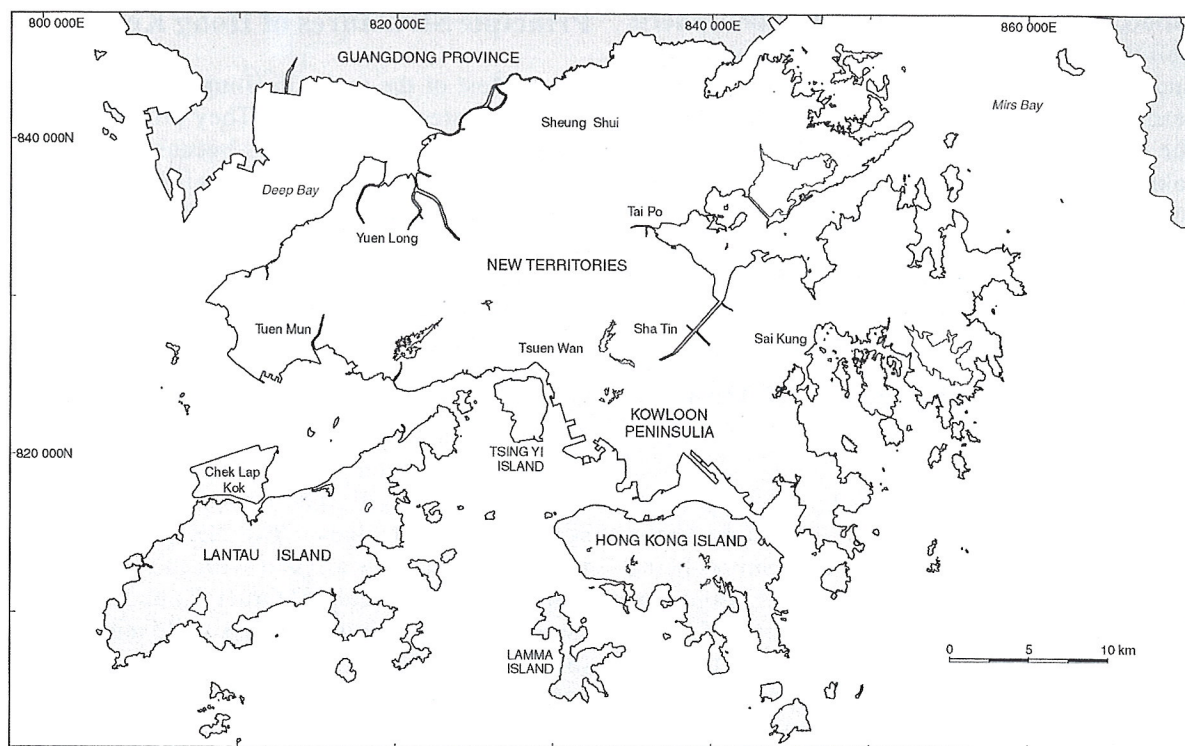


Fig. 3 Major areas of the Hong Kong SAR referred to in this paper

Topolineaments identified on the shaded relief map are shown in Fig. 5.

(i) E-W varying to ESE-WNW trending topolineaments

These topolineaments are scattered throughout the Sai Kung district. They are the least laterally persistent of the topolineaments in the district and are therefore regarded as minor structures. Typically, most are 0.5 to 1km in length. However, two exceptions are noted: one in the central part of Sai Kung, between Chek Keng and Cheung Sheung and the other one further to the north. Both coincide with known faults and can be traced for up to 5 km. The Chek Keng-Cheung Sheung fault is one of the most important faults within the district (Campbell & Sewell, 1997; Sewell *et al.*, 2000) and it is believed to have been an important control of volcanic and magmatic activity. The latter fault is cross cut in the middle by a NNE-SSW trending topolineament.

(ii) NE-SW varying to NNE-SSW trending topolineaments

The NE-SW trending topolineaments are the dominant structural features in the district. They are located mainly in the central part of Sai Kung. Most are sharp topographic depressions

and extend for up to 6km. Adjacent faults are about 1.5 to 2 km apart.

The NNE-SSW trending topolineaments are present throughout the Sai Kung District. They form negative topography. In the northwest of the district, a persistent topolineament extends 10km between Hoi Ha Wan and Tai Wan (Fig. 5). This topolineament is shown on the accompanying Engineering Geology Maps of the GASP Report Volumes VIII and IX. However, the continuity of this topolineament was uncertain and the fault was not specifically described in the reports. On the basis of its appearance and geometry, it may be a steeply inclined fault.

(iii) NW-SE trending set of topolineaments

This set of topolineaments is not commonly found in the district. However, one topolineament, in the centre of the district, extends for 6km parallel to the long axis of the High Island Reservoir, between Pak Tam Chung and Yung Shu O. This feature is cross cut and offset by NE-SW varying to NNE-SSW trending topolineaments.

(iv) N-S varying to NNW-SSE trending topolineaments

These topolineaments are present throughout the district, extend up to 5 km and

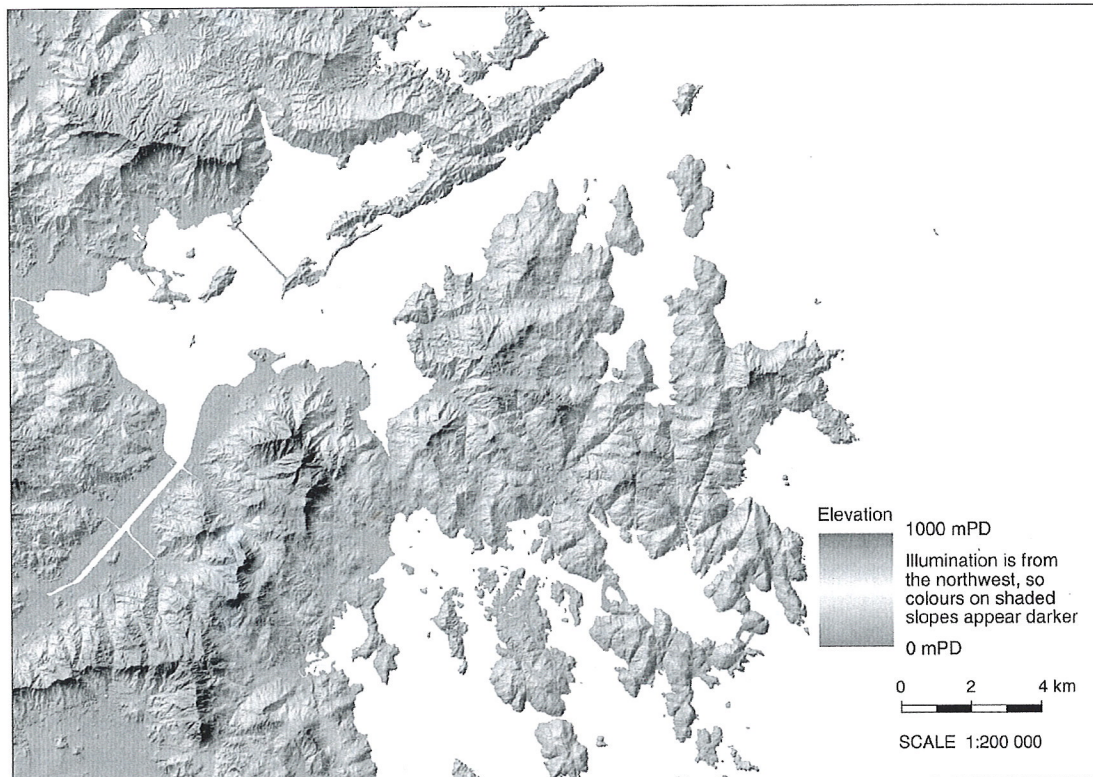


Fig. 4 Shaded Relief Map of the Sai Kung District, Eastern Hong Kong

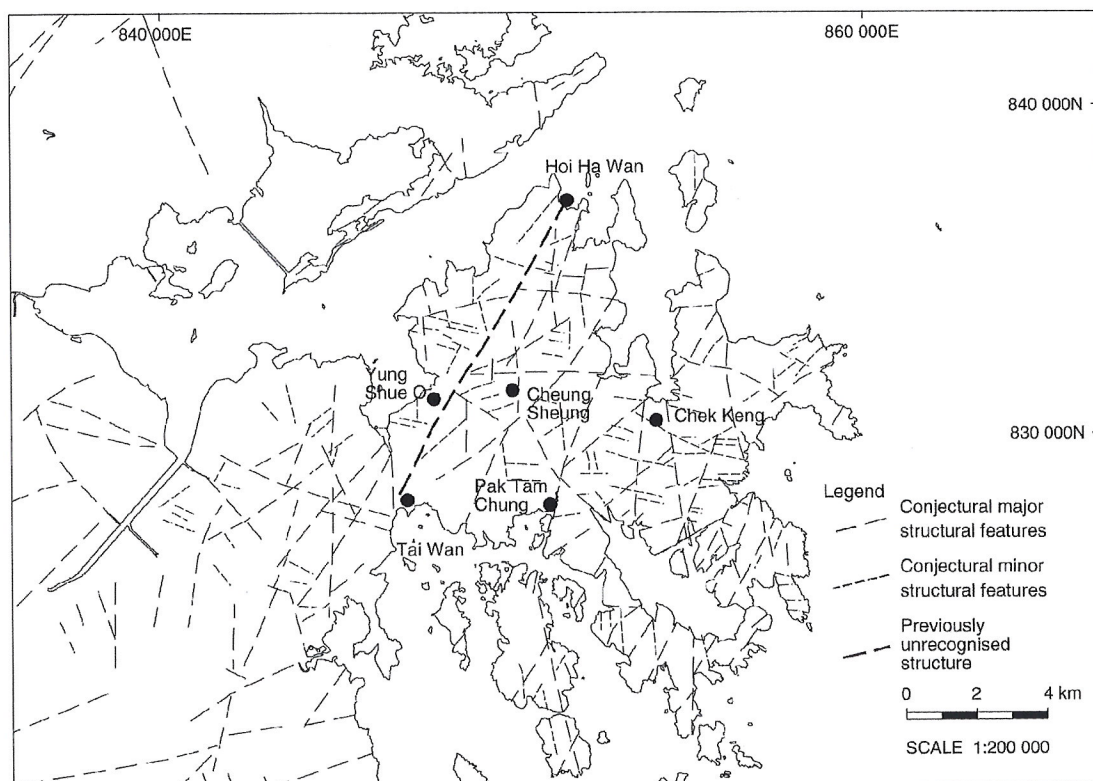


Fig. 5 Structural features of the Sai Kung District, Eastern Hong Kong (based on the shaded Relief Map)

are about 1 to 2km apart. They offset NE-SW varying to NNE-SSW trending topolineaments, with both apparent sinistral and dextral strike slip displacements.

To conclude, on the basis of cross-cutting relationships on the shaded relief map, the relative ages of the four sets of the topolineaments are as follows. The E-W varying to ESE-WNW trending topolineaments are the oldest, followed by the NE-SW varying to NNE-SSW trending and NW-SE trending topolineaments. The N-S varying to NNW-SSE trending faults are the youngest. However, some of the older topolineaments may have been re-activated by later events.

Conclusions

A high-resolution shaded relief map provides a useful basis for delineating major structural features on plan. Many features are more easily interpreted on the shaded relief map than they are on either aerial photographs or satellite images. Detailed interpretation has been undertaken for the Sai Kung District, and is now being extended across the Hong Kong SAR. However, it should be borne in mind that interpretations based solely on the shaded relief map are only preliminary and field checking is essential to confirm the nature of each topolineament.

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Confined Groundwater Zone and Slope Instability in Hillsides of Weathered Igneous Rock in Hong Kong

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Abstract

It is customary in Hong Kong to assume that the hydraulic conductivity of weathered igneous rocks decreases with depth or as the rock mass becomes less weathered. Generally groundwater flow studies for slope stability purposes treat the saprolite as an aquifer and the 'rock head', notionally the upper surface of a zone dominated by Grade III (GEO, 1987) or less weathered material, as an impermeable boundary. This paper examines published hydraulic conductivity data and groundwater observations that suggest that such a model may be inappropriate. Evidence is cited to show that, at least in some places, a more permeable zone may exist at depth, either in the lower saprolite or at rockhead. The groundwater flow regime in such a high hydraulic conductivity zone may be confined, resulting in higher water pressure in response to rainfall than might otherwise be expected. These high pressures may be responsible for a significant reduction in slope stability. An examination of the cross sections of some well-known landslides in Hong Kong revealed a chair-shaped rockhead profile. The paper goes on to show that misinterpretation of the hydraulic conductivity profile will lead to incorrect groundwater flow and slope failure models. The presence of a confined groundwater zone in the weathering profile would also be important for tunnelling, bored pile construction, and deep excavations. The discussion in this paper is based on cases in Hong Kong, but the conclusions and insights may be useful to hillslopes in other regions of similar geological conditions.

摘要

在香港，人們總是慣於認為風化的火成岩隨著深度增加或風化程度減弱，其滲透系數隨之減小。以評價斜坡穩定性為目的的地下水研究常因此將風化殘積土視作潛水含水層，而將基岩視作隔水層。本文分析研究了各類出版的滲透系數、地下水觀測資料，其結果表明這種潛水含水層模式值得商榷。資料表明，至少在某些斜坡，在殘積土與基岩界面附近有一層裂隙發育帶，該帶中的地下水可能是承壓的。在降雨期間，該承壓含水帶可能產生高出人們預料的孔隙水壓力，並因此而減少斜坡穩定性。

Introduction

Slope failure has long been the subject of local research but the study of the impact of regional hydrogeological conditions on slope stability in Hong Kong has received relatively little attention. The first and still the most comprehensive study of hillside hydrogeology in Hong Kong was the Mid-levels Study (GCO, 1982). Over 400 boreholes were installed in the Mid-levels area of Hong Kong Island between Glenealy and the University of Hong Kong and many hydraulic conductivity tests (borehole tests, infiltration tests,

pumping tests, and laboratory tests) were conducted. The hydraulic conductivity test data from all of the boreholes were plotted together (GCO, 1982). There is significant scatter but a trend of reducing permeability with depth is apparent. Leach & Herbert (1982) and Lerner (1986) developed finite difference numerical models for the Mid-levels area using over 30 node points to assist in understanding the hydrogeology of the steep hillside. Assuming that the granite bedrock was effectively impermeable, the models only simulated the saprolite and

colluvium regolith, which ranges in thickness from a few meters to about 40 m. Since the models were unable to reproduce the measured high water level, a recharge from the bedrock had to be assumed. Since the 1980s, computer techniques and numerical algorithms have advanced enormously. However, the understanding of the physical process of groundwater flow through a hillslope in Hong Kong has not significantly advanced. The idealization used by Leach & Herbert (1982) and Lerner (1986) remains the norm. Generally groundwater flow modelling still focuses on the so-called unconfined groundwater flow in the narrow strip of saprolite around the landslide scar but the recharge from the bedrock is entirely ignored.

A characteristic reduction in hydraulic conductivity with depth has been widely assumed in practice in Hong Kong since the 1970s (Nash & Arthurton, 1987; GEO, 1996). The default hydraulic conductivity profile is a permeable saprolite on an impermeable bedrock, though perching may be assumed at the base of the colluvium, if present. Either a gradual or step decrease in hydraulic conductivity with depth can only lead to an unconfined aquifer model. As the regionally influential and internationally cited Geotechnical Manual For Slopes states (GEO, 1994): "in Hong Kong, aquifers are usually unconfined".

Evidence of a permeable zone in igneous rock weathering profiles

Not all local hydraulic conductivity data is consistent with the default model. In the following some non-conforming published hydraulic conductivity data and groundwater observations are reviewed.

Highly permeable zone indicated by hydraulic conductivity profile at a deep excavation site

Davies (1987) presents data from borehole rising and falling head tests, packer tests and pumping tests at the MTRC Wanchai station construction site. The site was described as being underlain by fill, marine deposits and alluvium, residual soil, completely decomposed granite (CDG), highly decomposed granite, and granite bedrock (Fig. 1). The measured hydraulic conductivity profile is shown in Fig. 2. The hydraulic conductivity of the fill material at the top is greater than 10^{-5} m/s. Below the fill material, the hydraulic conductivity increases with depth in the CDG, achieving a maximum at 50 m depth, where Grade III rock dominates, and then decreases with depth in the Grades I and II rock. The hydraulic conductivities estimated from the pumping tests show a higher permeability zone in the 'Lower CDG' (Table 1).

These results are not unreasonable. It could well be that a more permeable region exists in the lower saprolite and upper weathered bedrock zone due to the presence here of well developed jointing systems, which are hydraulically conductive.

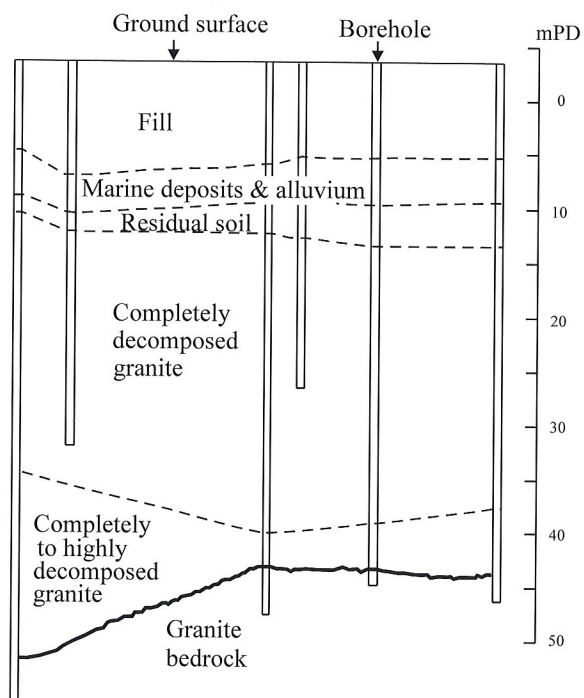


Fig. 1 Geological cross section at the construction site in Wanchai, Hong Kong (from Davies, 1987)

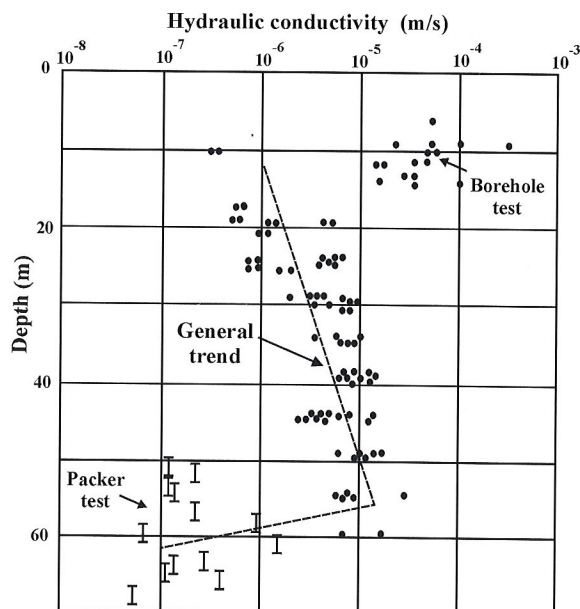


Figure 2: Variation of hydraulic conductivity with depth at the construction site in Wanchai, Hong Kong (from Davies, 1987)

Zone	Permeability (m/s)
Fill	$>10^{-4}$
Marine deposits	5×10^{-5}
Upper CDG	5×10^{-7}
Lower CDG	5×10^{-6}

Table 1 Hydraulic conductivity in the weathering profile at a construction site for the MTRC Wanchai station, Hong Kong (Davies, 1987)

Permeable zone in tunnel construction

The existence of a permeable zone at depth is suspected from groundwater conditions observed in the site investigation of the hillside at the southern portal of the Aberdeen Tunnel and during tunnel construction. Twist & Tonge (1979) note: "It appeared that an artesian condition could exist in the lower part of the hillside where the base of the hill was covered by residual soil and colluvium, and the main source of water and water pressure was from the more permeable zone at the weathered rock and fresh rock contact. Following rains, this zone could have sharply increased piezometric levels because of its continuity in an uphill direction, where it could be charged by infiltration in areas of thin colluvial or residual soil cover". During construction it was noted that "a sharp interface between the sound and decomposed monzonite produced water inflows that could only be controlled by pumping" (Bevan, 1984).

Increasing permeability with depth was revealed in the construction of the Hong Kong and Shanghai Bank seawater tunnel in Central district of Hong Kong. Cowland & Thorley (1985) say that "... a considerable thickness of completely to highly decomposed granite exists in the area. ... It is interesting to note that whilst the permeability tests undertaken in this material showed a wide variation of values, there was a trend of increasing permeability with depth". The high hydraulic conductivity zone is confirmed by Troughton *et al* (1991): "A series of constant head water extraction tests which had previously been done in the completely decomposed granite also showed (that) at a depth of 10 m above rockhead the average permeability was 6×10^{-6} m/s whereas close to rockhead it was 6×10^{-5} m/s".

Highly permeable zone in bedrock indicated by piezometric response

The weathering profile at the former coastal site in Wanchai or the southern portal of the Aberdeen Tunnel may not be characteristic of that in the hillside. Furthermore, borehole hydraulic conductivity tests are prone to uncertainties of various kinds. More reliable observations of hillside hydrogeological characteristics are needed. Since the hydraulic conductivity characteristics of the weathering profile will be reflected by the piezometric response to rainfall, the response at different depths within the profile may give insights into the distribution of hydraulic conductivity with depth.

Fig. 3 shows the piezometric response to rainfall with depth near Scenecliff, No 35, Conduit Road in the Mid-levels between July 10-16, 1980 (GCO, 1982). The details of the vertical locations of the piezometer tips and the geology of the site are shown in Fig. 4. The tips of the piezometers are located in what is described as colluvium, decomposed granite, and granite bedrock. More detailed information on the geology of the site and

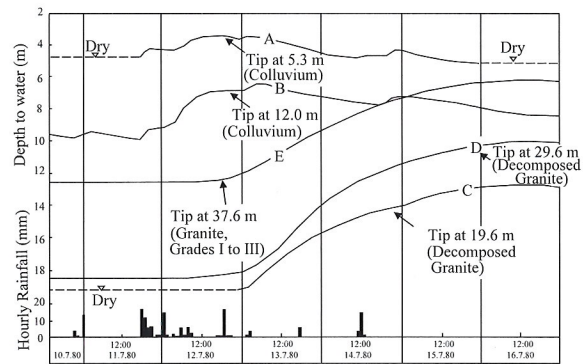


Fig. 3 Hourly response to rainfall of piezometers at ML 113 in the Mid-Levels, Hong Kong (GCO, 1982)

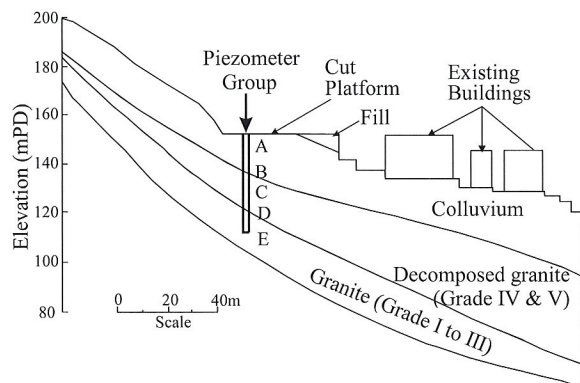


Figure 4: Simplified geological section through the piezometer group of ML 113 (Pop *et al*, 1982)

location of the piezometer groups can be found in GCO (1982). Before the rainfall began, Points D and E were in the regional saturated zone. Point B had a measurable water level and therefore was in a local saturated zone. The two saturated zones were separated, since Point C was dry. Most of the rain fell on July 11 & 12. The water level at Points A & B showed a fairly immediate rise. By the end of July 12, Point E, at the lowest elevation, began to rise, then Point D, followed by Point C. Point E began to rise when Point C was still dry. As infiltration proceeded, the two saturated zones met. When the water level at Points A & B began to decline, the water level at Points D, C, E increased quickly and reached a maximum by July 16, by which time there had been no rain for two days.

The most plausible hypothesis to explain the above observations is as follows:

- 1) The significant early rise in pressure at Point E in the bedrock was mainly caused by pressure transmission through 'Grade III' after infiltration in the remote upper part of the slope, which suggests that there is a rather permeable zone near the bedrock.
- 2) There was a significant delay in pressure response near the bedrock to rainfall.
- 3) The change in hydraulic head in the bedrock was much greater than that in the saprolite. A considerable vertical upward flow was generated after rainfall.

4) The bedrock and the saprolite near the bedrock became confined after July 13.

If the above hypothesis is correct, a high conductivity zone may exist at rockhead in this part of the Mid-levels area.

Possible confined groundwater zone indicated in landslide studies in Hong Kong

It is of interest to know whether any of the Hong Kong landslides which have been investigated in detail show a confined aquifer. So far, the reports of ten large landslides have been examined. Three reports give a fairly detailed description of the hydrogeology. These sites are Tsing Yi (1) (TY), New Territories (GCO, 1983), Tuen Mun Highway (TMH) at Chainage 550 near Tsuen Wan, New Territories (Choot, 1984), and Siu Sai Wan (SSW), Hong Kong Island (Ho and Evans, 1993).

In summary these studies showed that weepholes or shallow horizontal drains remained dry after rainfall in the slopes at TY and SSW, but that deeper horizontal drains produced water. Perhaps this is because the deeper drains connected with groundwater in the bedrock.

At TY and TMH, water level measured in the piezometers in the completely decomposed rock did not show a large response to rainfall. For example, a shallow piezometer in the highly decomposed granite near the top of the cut slope at TY showed a rise of about 1.5 to 2.0 m after a rainfall. However, the groundwater level in a piezometer installed in the bedrock near the toe of the slope showed a rise of 7 m in response to the same rainfall. Perhaps this is because of the confining effects of the saprolite or perhaps it was a cleft water pressure that was by chance intercepted.

In SSW piezometers above bedrock showed practically no response to rainfall, while those in or near the bedrock showed a stronger response to rainfall (Ho & Evans, 1993). An upward groundwater flow from the bedrock was noted, which may have been caused by either confinement of a low permeability zone in the weathered rock profile, or because this slope lies at the discharge zone of a regional groundwater flow system.

Permeable zones in igneous rocks noted in the literature

Looking outside the narrow confines of Hong Kong, it is interesting to note other references to permeable zones in the weathering profile of igneous rocks. The sequence of previous and impervious layers in slopes in residual soils is described by Terzaghi and Peck (1967) in their classic textbook as follows: "Within the zone of weathering of the insoluble types of rock, it is by no means uncommon for the coefficient of permeability of the weathered rock to increase from very small values near the ground surface to maximum values close to the boundary between weathered and sound rock. Thus the zone of rock weathering forms a relatively impervious

skin resting on a pervious layer. If water enters the previous layer through a gap in the skin or through open fissures in the sound rock, artesian conditions may develop in the pervious zone and the impervious top layer may slide down the slope even if the inclination is very gentle".

Such a sequence was later described in detail by Deere and Patton (1971), who regard the more permeable zone in the middle of a weathering profile of intrusive igneous rocks as a commonplace occurrence. They stated that: "this zone is commonly very permeable and water losses are often noted by drillers when they reach this zone" (Deere and Patton, 1971). They also believed that slope instability is often associated with such a permeable zone: "It is the sequence of a low strength, low permeability zone overlying a high permeability zone, both of which are lying subparallel to the ground surface, that is the main unifying aspect of stability problems of slopes in residual soils" (Deere and Patton, 1971).

Shape of the bedrock in some slope failures

The slip surfaces of most of the deep-seated and slow moving landslides in Hong Kong appear to be controlled by the boundary between completely decomposed rocks and moderately decomposed rocks. After examining the cross sections of some well-known landslide sites, a strikingly common feature is observed. That is, the rockhead profile is chair-shaped. Fig. 5 presents the interface of the saprolite and the bedrock in 8 well-known failures in Hong Kong (GCO, 1983; Choot, 1984; Martin, 2000; GCO, 1989; Ho & Evans, 1993; GEO, 1998a; GEO, 1998b; Sun & Campbell, 1998; GEO, 2000). Most of the failures are ductile or deep-seated landslides (Malone, 1998). While the interface is generally parallel to the slope surface, at the toe region, the interface becomes rather flat (Figs. 5C, E, H), or depressed slightly (Figs. 5A, B, D, F, G). The saprolite in most of the slopes becomes thin toward the toe. The sliding surface is usually located above the flat or depressed areas. It is unclear if this shape is simply a coincidence or has some important implication for the failure mechanisms.

A conceptual model

Based on the previous discussion about the hydraulic conductivity distribution and the shape of the rockhead, a conceptual hydrogeological model is proposed in Fig. 6 for situations where a permeable zone exists at depth. The upper saprolite behaves as an aquitard and a confined aquifer exists in the lower saprolite, or the notional rockhead zone. The aquifer should not be understood as the typical confined aquifer used in traditional hydrogeological modelling. This aquifer may be only half-full, or even completely dry in the dry season, but may become fully confined following periods of heavy rainfall.

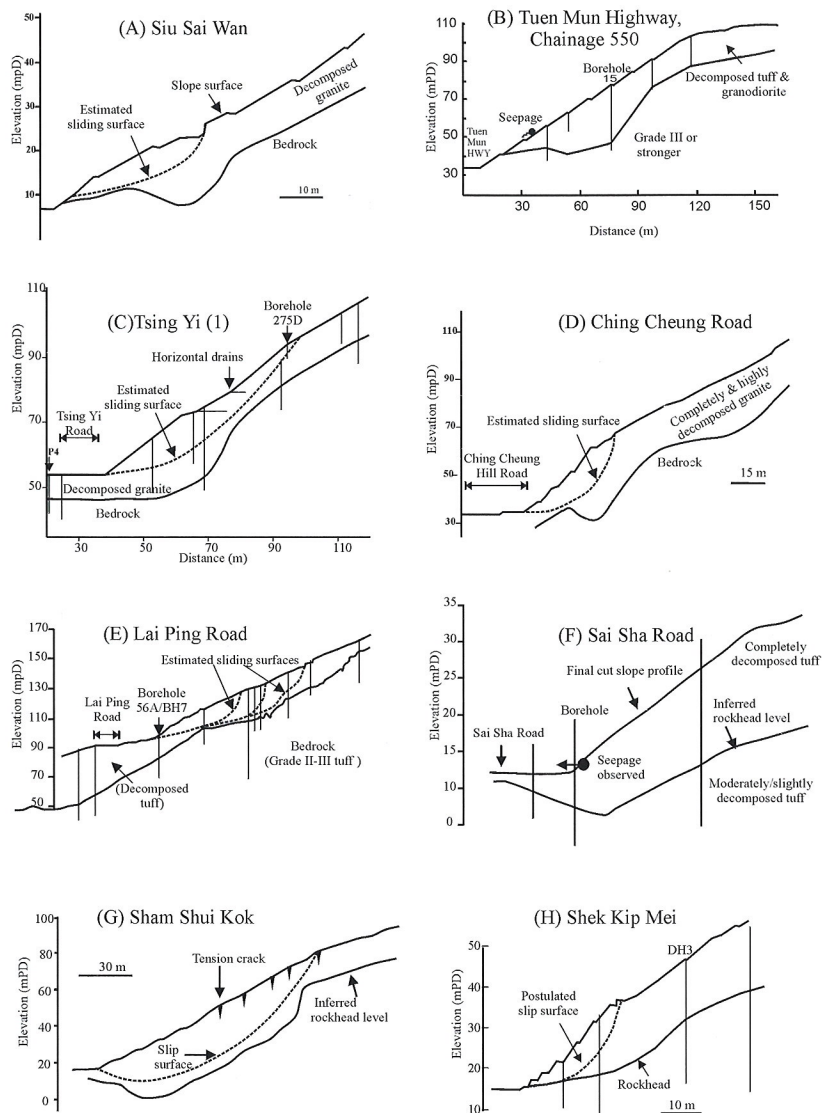


Fig. 5 Chair-shaped rockhead in cross-sections of some well-documented landslides in Hong Kong (simplified from GCO, 1983; Choot, 1984; Martin, 2000; GCO, 1989; Ho and Evans, 1993; GEO, 1998a; GEO, 1998b; Sun and Campbell, 1998; GEO, 2000)

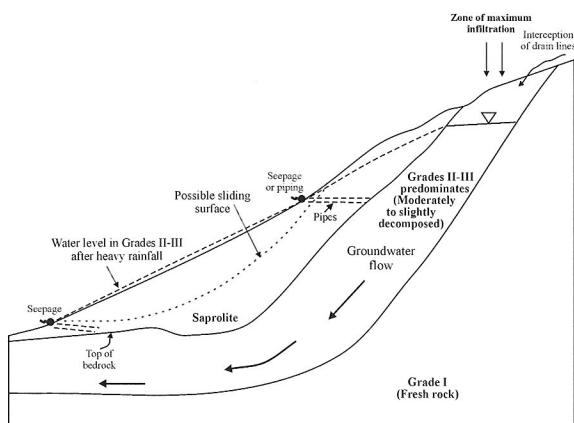


Fig. 6 A conceptual model of some deep-seated landslides in cut slopes of weathered igneous rocks in Hong Kong

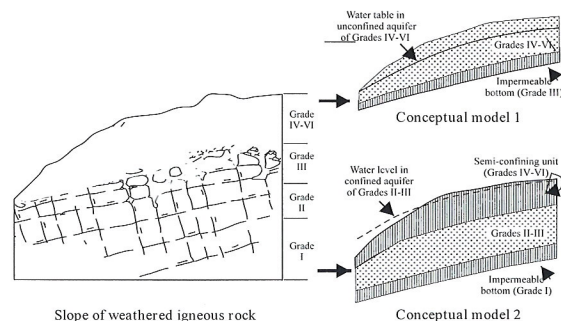


Fig. 7 A weathered igneous rock slope and possible hydrogeological conceptual models

Implications of a confined aquifer on slope hydrogeology

The pore pressure rise may be very high in the confined permeable zone following exceptionally heavy rainfall. Such high pressures, transmitted perhaps via rock discontinuities, might aid the formation of soil pipes as shown schematically in Fig. 6. The occurrence of soil pipes in saprolite may be an indicator of confinement. This conclusion is different from the traditional idea (GCO, 1983) that soil pipes in saprolite are believed to be an indicator of high permeability of the saprolite itself. Critical water pressures, perhaps even artesian pressures, may be generated in saprolite at the toe of the slope.

A piezometer in the saprolite may still show a measurable water level, but its response to rainfall is usually insensitive or rather random, depending mainly on the local hydraulic condition around the piezometer and the degree to which the soil is disturbed due to installation of the piezometer. Usually piezometers in this zone cannot accurately represent the water level pattern.

The bedrock is essentially a fracture aquifer, which can be extremely heterogeneous and anisotropic. In many cases, it crops out at the upper part of the hillside and forms a zone of maximum infiltration (Terzaghi & Peck (1967; Twist & Tonge, 1979). Infiltration may be facilitated by boulder-filled rock cut gullies, which are commonplace. A piezometer at rockhead will therefore be more sensitive to rainfall than one installed in the overlying saprolite. For a fracture aquifer, the hydraulic conductivity can be great, but the storativity may be generally low. Therefore, the pressure can build up quickly in heavy rainfall periods and can dissipate quickly after rainfall, if the slope has a good drainage system. It is worthwhile to note that, for slope instability, it is not the amount of groundwater, but the amount of pore pressure which is generated from groundwater which matters.

Slope stability implications of a permeable zone

The reliability of a slope stability assessment usually depends on the reliability of the pore pressure information. Different hydrogeological models may give quite different pore pressure predictions. The water pressure rise following rainfall may be much higher in a confined hillside aquifer than in an unconfined aquifer.

Fig. 7 shows an igneous rock weathering profile and two different conceptual hydrogeological models. If the bedrock is assumed to be impermeable, then Model 1 in Fig. 7 will follow. This is the typical model assumed in local practice in Hong Kong and it represents an unconfined system. If the lower saprolite zone, or the zone below the notional 'rockhead' is assumed to be more permeable than the ground above and below, then Model 2 in Fig. 7 will follow, which is a confined or semi-confined aquifer system.

These two conceptual models have different implications for slope stability. Model 2 may yield a much

higher and more rapid pore pressure rise than Model 1. When water pressure information for a slope is unavailable, as it commonly is, it is the local practice to assume a worst case. Usually, the worse case assumes that the water table is as high as the ground surface. This may well be the worst case for Model 1, but it is not the worst case for Model 2. Since the aquifer in Model 2 is confined, the piezometric head can be much higher than the ground surface.

Different conceptual models also have different implications for the choice of measures to improve slope stability. If Model 1 applies, horizontal drains drilled into saprolite may in theory improve stability, but if Model 2 applies saprolite drains may be ineffective. For Model 2, stability will be improved in theory by installing drains deep enough to intercept the permeable zone.

Conclusions and recommendations

Generally, in groundwater flow modelling for slope stability studies in Hong Kong, the saprolite has been treated as an aquifer, with perching horizons within it or at its base whilst a notional bedrock is assumed and treated as an impermeable boundary. Not all local hydraulic conductivity data is consistent with this model. Evidence presented here shows that in places a permeable zone is present at depth. This paper has also examined the shape of the rockhead in some of the well known landslide sites, and it appears that the chair-shaped rockhead is a common feature of the deep-seated landslides. The interface between the saprolite and the bedrock is generally parallel to the slope surface. At the toe of the slope, the interface becomes rather flat or depressed slightly. The sliding surface is usually located above the flat or depressed areas. Further studies are needed to see if this feature has some implication for the failure mechanisms.

Based on the hydraulic conductivity profile and the chair-shaped rockhead, a conceptual hydrogeological model for slopes has been postulated, and the importance of a correct hydrogeology model discussed. Groundwater flow simulation can never be right and the modelling results are meaningless if the conceptual model is wrong.

If a confined groundwater zone is present there are implications for slope engineering. The reliability of a slope stability assessment usually depends on the reliability of the pore pressure information. Different hydrogeological models may give quite different pore pressure predictions. The water pressure rise following rainfall may be much higher in a confined hillside aquifer than in an unconfined aquifer. An effective water depressurizing system, which intercepts the groundwater in the relatively more permeable zone, would be a direct way to increase the stability of such a slope.

To fully understand the hydrogeological behavior of a slope, the geological site investigation should cover

an area larger than the vicinity of a landslide. The study area should cover preferably an entire catchment. Vertical boreholes should be drilled into the bedrock of Grade I, instead of only rock of Grade III. Because of the potential for unexpectedly high water pressures the presence of a confined aquifer within the weathering profile would also have implications for tunnelling, bored pile construction and deep excavations.

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COMMENT & REPLY

Discussion on Weathering profile development below the Yuen Long Plain, western New Territories, Hong Kong by Owen, R.B. & Shaw, R. Hong Kong Geologist, vol. 5, 1999, pp 1-11

A.W. Malone writes: The concept of the weathering front is potentially useful in local practice but we must have a clear understanding of what we mean by the term 'weathering front'. If we are to make contour maps of the weathering front we need a set of rules by which the weathering front elevation may be determined consistently from borehole logs in typical weathering profiles.

The authors' determination of the 'weathering front' normally requires "drilling for at least 5 metres into Grades I to III rock material.". Bands of weathered rock less than 1 metre thick are acceptable below the weathering front but thicker bands are not. The former criterion is justified by reference to Geoguide 3. The latter is explained in terms of corestones and widened joints. Corestones are "occurrences of Grades I to III material that were separated from each other, and the weathering front, by at least 1 metre of weathered rock material. Bands of weathered rock less than 1 metre thick were considered to be widened joints."

I have reservations about the authors' definition:

(i) We know of the existence of corestones having greater vertical dimension than 5m. If only 5m of rock is penetrated how do we know that a band of Grade IV or V material of thickness greater than 1m does not exist just beneath?

(ii) Where a substantial thickness of rock is penetrated followed by a band of Grade IV or V material of thickness greater than 1m, the authors' definition classes the rock as corestone. We know from tunnelling that bands of Grade IV or V material of thickness greater than 1m may exist in rock at depth. Did the authors adopt a maximum 'corestone' vertical dimension?

(iii) We know that corestones can occur separated from each other by less than 1m of Grade IV or V material.

I do not believe the authors should be citing Geoguide 3 Guide to Site Investigation (Geotechnical Control Office, 1987) in support of the 5m of rock in their definition of weathering front. The authors say the 5m rock drilling depth referred to in their definition of weathering front is adopted from a criterion in Geoguide 3. In the course of drafting this letter I have not re-read Geoguide 3 word for word so will assume the authors are referring to Geoguide 3 Section 10.7.1, a passage about deciding depth of ground exploration for civil engineering sites. The section states "In Hong Kong it is common practice to drill into rock for a depth

of at least 5 m to establish whether corestone, boulder or bedrock has been encountered. However, the final depth of drilling will depend on the need to prove bedrock. In some cases, it will be necessary to drill deeper than 5m to establish conclusively the presence of bedrock, for example, in investigations for end bearing piles.". It should be appreciated that the type of pile for which it was "common practice to drill into rock for a depth of 5m ." is an end bearing pile founded on 'bedrock'. So clearly Geoguide 3 Section 10.7.1 cannot be said to endorse the practice of proving rock by drilling only 5m into Grades I to III rock material.

Even if we had some civil engineering authority for the 5m of rock requirement we still need to know that the adoption of a slightly different thickness in the definition of weathering front would not have a marked effect on weathering front elevation as determined from borehole logs. Therefore, will the authors say what would be the effect on elevation of the weathering front in a sample of their boreholes, say in corestone and non-corestone bearing ground of typical lithologies, of taking slightly different definitions of weathering front, e.g. 6m or 8m of rock, rather than the 5m of rock which they have chosen to use. Also what is the effect of taking a weathered band of 0.8m or 1.2m thickness rather than 1m to be a 'widened joint'?

In conclusion I believe we need to have a precise and complete definition of the concept of weathering front for practical application. I appreciate the authors' difficulties in constructing a definition which is viable for all situations and have no better definition to offer. If we cannot give a precise and complete definition which works in corestone-bearing profiles then perhaps our concept is flawed in these conditions.

R. Shaw & R.B. Owen reply: The authors thank A.W. Malone (AWM) for raising a discussion of the weathering front concept. We share AWM's concern that a great deal of misunderstanding is associated with the concepts and definitions of the weathering front, and the analogous terms bedrock and rockhead that are used by the mining and engineering fraternities. Consequently, the use of any one of these terms is potentially fraught with difficulties, problems that are compounded by individual interpretations and applications of the concepts. The authors strongly

recommend that, to avoid potential ambiguity, it is important that the use of any one of these terms in a report or publication is accompanied by clear working definitions. This precaution will ensure that readers know what feature is being referred to and what limits or criteria are being applied. This was done in our recent papers (Shaw, 1997; Owen & Shaw, 1999, 2000). Another caution, shared in common with geological mapping, is the scale problem inherent in the concept of the weathering front. Depicted at the regional scale, the weathering front will appear as an undulating, but smoothed, surface. Clearly, small scale maps, be they geological maps or contour maps of the weathering front topography, should not be used for site specific purposes. In contrast, at a large, site specific, scale the weathering front will exhibit a more intricate topography. Pronounced irregularities of the weathering front are to be expected on large scale maps because widened vertical joints and local structures assume greater importance as true scale is approached.

Notwithstanding the above reservations, we began our studies of the weathering front on the premise that, with the considerable wealth of borehole data available, Hong Kong presented an ideal opportunity to attempt the exercise of modelling regional variations in both the weathering front topography, and the thickness of the weathered profile. The study by Shaw (1997) was the first step in a process of evolution and refinement of the understanding of the weathering front in Hong Kong, a study that was extended to Yuen Long by Owen & Shaw (1999) and to Tuen Mun by Owen & Shaw (2000). This discussion forms an important part of the development of that understanding.

In reply to the specific points raised, the authors have the following comments.

With regard to point (i) about the existence of corestones greater than 5m in vertical extent, as elaborated below, we adopted 5m as the cutoff point in order to include most of the Hong Kong borehole database that reached and penetrated rock. We agree that corestones greater than 5m vertical dimension do exist, but believe them to be sufficiently rare to be all but discounted. Unfortunately, even if a limit of 10m or 15m was selected, there remains the (albeit remote) possibility that a (vertically) thick weathered band might be present immediately below the base of the hole. However, we contend that the question "what if" arises whatever limiting values are selected.

Further, despite the commonly held belief to the contrary, we wish to emphasize that corestones are not the norm in weathered profiles. Gamon & Finn (1986) pointed out that they did not find the regular vertical zonation in the weathering profile reported by Ruxton & Berry (1957). Similarly, Shaw (1997) found that an abrupt transition to bedrock from a corestone free profile

was dominant in Kowloon. This point is developed further below.

In reply to point (ii) about defining the limiting thickness of the weathered band, again the question comes down to the values chosen. A limit of 1m was selected by Shaw (1997) based on practical experience. Interestingly, this value closely corresponds to a vertical dimension of 0.9m (3 feet) recommended by Yokley (1991) for measurement in rock excavation contracts. According to his specification, a vertical profile that contains "soil seams" of 0.9m or less would be regarded as rock. It is important at this stage to emphasise the distinction between vertical and horizontal dimensions. Due to the nature of the weathering process, penetrating from the surface downwards, vertical joints are usually more weathered, and thus widened, than horizontal joints. Tunnelling, which is usually carried out horizontally, will commonly encounter widened vertical joints, but less commonly widened horizontal joints. The latter are believed to be more the province of shaft driving.

With regard to point (iii), we do not agree with the statement that "corestones can occur separated by less than 1m of Grade IV or V material". Resolution of this point hinges upon the definition of a corestone. The original definition of a corestone is credited to David Linton (1955) who considered a corestone to be "an ellipsoidal or broadly rectangular joint block of granite formed by subsurface weathering in the same manner as a tor, but entirely separated from bedrock". The present authors feel that whether one adopts 0.8m, 1m, or 1.2m as the definition of "entirely separated" is more a matter of semantics than of earth sciences. Although we accept that the thickness adopted may have important consequences for certain engineering applications, we believe that the limit selected does not materially affect the geological concept and its regional application.

With regard to the depth of drilling into bedrock, the figure of 5m was adopted simply because of the nature of the database. Ideally, if all boreholes had penetrated for 10m, 15m or even 20m into bedrock, then these limits would have been used. The 5m figure, and the reference to Geoguide 2 (GCO, 1987), was presented by way of background to readers unfamiliar with Hong Kong practice, as an indication of the nature, and the attendant reliability, of the borehole data available. Because the study was based on existing borehole data archived in the GIU of the Civil Engineering Department, and because the majority of boreholes in Hong Kong do not penetrate more than 5m into bedrock, a limit of 5m was a pragmatic choice. Otherwise, apart from a limited number of longer (deeper) boreholes for a few projects such as the Strategic Sewage Disposal Scheme (SSDS), no data would have been available for this or

other (Shaw, 1997; Owen & Shaw, 2000) studies of the weathering front.

Clearly, it is impossible to confidently answer the penultimate question posed in paragraph 5. However, from our point of view, the existence of a continuous vertical run of Grade I to III rock of 5m, even with widened vertical joints bounding it laterally, would be an adequate definition of bedrock. A fuller, more confident answer would require an extended research project that could call upon a body of data that is not available in Hong Kong, because most boreholes are too shallow.

In answer to the final question, returning to the point about the choice of thickness of a weathered band, it was found that the definition rarely needed to be applied. Of the 4730 boreholes assessed by Shaw (1997) in the Kowloon weathering study, only 25% contained corestones as defined. Hence, it was not necessary to apply the definitions being discussed in 75% of the cases. Comparable figures for the Tuen Mun and Yuen Long study areas were 10% (Owen & Shaw, 2000) and 22% (Owen & Shaw, 1999) respectively. The conclusion to be drawn from these findings is that varying the chosen thickness of the weathered band could only affect the interpretation of the elevation of the weathering front over about 25% of the study area in Kowloon, 10% of the study area in Tuen Mun, and 22% of the study area in Yuen Long. Given other uncertainties, such as the reliability of the original logging and the risks inherent in interpolating between widely spaced boreholes, the authors feel that the choice of weathered band thickness would have only a minimal effect upon their published models of the regional weathering front topography.

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