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## Preliminary Investigation Of Zircon Morphology Of Granitoid Rocks In Hong Kong

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### Abstract

Investigations of zircon size, typologic distribution of zircon populations and other heavy mineral assemblages of granitoid rocks in Hong Kong have been carried out. Elongation of zircon (L/B ratio) is mostly around 2 to 2.5, but may up to 9. G, P<sub>1-5</sub>, D, S<sub>23-25</sub> and J<sub>3-5</sub> (after Pupin, 1980) are found to be the main zircon population types. Zircon crystallization cycle can be of long duration covering the entire magmatic stage with transparent zircons crystallized earlier than the translucent ones. Based on the characteristics of distribution of zircon typological populations as illustrated by Pupin (1980), and on the basis of the petrogenetic classification proposed by Pupin, most granitoid rocks can be attributed to subalkaline to alkaline series granites of mainly mantle origin, but alkaline minerals can not be found in the granitoid rocks.

### 摘要

本文探討香港花崗岩類岩石中的鋯石大小，鋯石群型分布及其它重礦物組合。鋯石伸長系數大多在 2 至 2.5，可大至 9。G，P<sub>1-5</sub>，D，S<sub>23-25</sub>，及 J<sub>3-5</sub> 等型態是主要的鋯石類型。鋯石的結晶旋回可包含整個岩漿期。於早期結晶的是透明的鋯石，其後是半透明的鋯石。據查明的鋯石群型分布特徵，依 Pupin 的成因分類，大多數香港花崗岩類岩石歸屬於 Pupin 主要是地幔成因的次鹼性至鹼性系列花崗岩，但花崗岩類岩石未見有鹼性礦物出現。

### Introduction

Zircons have been used frequently for studies of genetic relationships between igneous bodies. It is believed that zircon populations for chemically similar igneous rocks from a single magmatic source usually show similarities, yet are dissimilar for rocks derived from different magma sources. With distinct habits and morphological characteristics, zircon crystals are easily measured for statistical analyses.

Zircon crystals from granitoid rocks in Hong Kong have been dealt with in an earlier publication (Nau, 1988). In this paper, apart from the common characteristics of size, shape and colour, attention is also given to zircon typomorphic characteristics, which may yield clues to the petrogenesis of granitoid rocks as described by Pupin (1980). In addition, a sample of crystal tuff (with hornblende) is also dealt with for reference.

### Granitoid Rocks and Crystal Tuff (with Hornblende)

Plutonic rocks in Hong Kong include granite, granodiorite and quartz syenite. There are also minor granitic intrusions such as feldsparphyric rhyolite and quartzphyric rhyolite. Classification of the plutonic granitic rocks in Hong Kong is, in one way, simply based on modal composition and grain size (Addison, 1986; Strange, 1985; Strange and Shaw, 1986). In yet another manner, on the basis of whole-rock major and trace element geochemistry, field and petrographic characteristics, the Hong Kong Granites have been divided into Lamma Suite (older suite) and Lion Rock Suite (younger suite). The Lamma Suite includes the Tai Po Granodiorite and Sung Kong Granite. The Lion Rock Suite is divided into three subgroups. Subgroup I (the oldest subgroup) includes Tai Lam and Tsing Shan granites. Subgroup II comprises the Sha Tin, Lantau plutons and quartz syen-

ite. Subgroup III includes the Kowloon, Chi Ma Wan, Stanley, South Lamma, Mt. Butler, and Kwun Tong plutons (Strange et al. 1991, Sewell and Langford 1991, Sewell et al. 1992).

Grain sizes of granitic rocks vary from fine- to coarse-grained. The main constituents of granitic rocks are K-feldspar, plagioclase, quartz and biotite. Granodiorite, including fine- to coarse-grained and sometimes megacrystic varieties, is composed of plagioclase, K-feldspar, biotite, quartz and hornblende. Quartz syenite is fine- to medium-grained, sometimes megacrystic. The main component is K-feldspar together with some biotite and quartz in minor amount. The mineral composition of feldsparphyric rhyolite is similar to that of plutonic granitic rocks. The granitoid rocks are of Upper Jurassic age. According to radiometric age determinations by Chandy and Snelling (in Allen and Stephens, 1971) and by Sewell et al. (1992), and by fission track dating (Nau, 1988) the absolute age of granodiorite is older than granitic rocks. Quartz syenite intrudes into granites and granodiorite. The intrusions of quartz syenite may belong to several phases which predate or postdate certain granite plutons (Strange and Shaw, 1986). Granite and granodiorite are intruded by feldsparphyric rhyolite.

The crystal tuff (with hornblende) concerned belongs to the Yim Tin Tsai Formation of Repulse Bay Volcanic Group of Lower Jurassic in age. The mineral composition of the crystal fragments is somewhat similar to that of granodiorite.

### Sampling

Twenty-three samples were collected from highly to completely weathered granitoid rocks (Figure 1). Ten of them were collected previously and labelled from A to J (Table 1) as reported in an earlier publication (Nau 1988). Among these samples, nineteen are from granite, two from granodiorite, one from quartz syenite, one from feldsparphyric rhyolite dyke, and also one from crystal tuff (with hornblende). Rock descriptions of the twenty-four samples, labelled from 1 to 24, are given in Table 1 together with corresponding names for granitoid rocks designated by Allen and Stephens (1971) and pluton-based nomenclature for Hong Kong granites (Strange et al. 1991, Sewell and Langford 1991, Sewell et al. 1992).

### Field and Laboratory Procedures

Field and laboratory procedures for obtaining zircon and other heavy minerals with SG greater than 3.3 have been given in an earlier publication (Nau 1988).

### Zircon Crystal in Granitoid Rocks and Crystal Tuff (with Hornblende)

#### (i) Colour

Zircon crystals have been detected in all sam-

ples. Zircon crystals in a sample may be colourless but are usually pale in colour, e.g. buff (sometimes with orange tint), orange-yellow or yellowish brown. Some are iron stained. Colourless zircon is transparent, the buff one is semi-transparent to translucent, while the orange-yellow, yellowish brown and iron stained ones are translucent to subtranslucent (or nearly opaque).

#### (ii) Shape

Almost all the zircon crystals are sharp prismatic (stubby or long slender) euhedra. Some are broken into fragments, which may probably be due to crumbling of weathered rock sample during panning. Only a few grains of zircon in megacrystic fine-grained granite (samples 3, 4, 10) and granodiorite (sample 9) display slightly rounded edges.

#### (iii) Inclusions

Solid, gas and liquid inclusions have not been examined in this study. However, black inclusions of ilmenite (or rutile and other black minerals) in zircons are outstanding under binocular microscope (samples 11, 14, 17, 20, 21).

#### (iv) Abundance

Approximate zircon contents in granitoid rocks vary greatly from place to place (Table 1). Generally, zircon is less abundant in megacrystic fine-grained granite. It is more abundant in sample 14 (granodiorite) than in others.

#### (v) Elongation

Zircon elongation (L/B ratio) was made by measurement of length (L) and breadth (B) under binocular microscope with a micrometer (for previous sample A to J, re-measurements have been made). Measurement of zircon euhedra is usually more than 100 grains and the maximum is 359 grains. For samples with less zircon euhedra, measurement is less than 100 grains and the least is 12 grains (sample 6).

For all the granitoid rocks, average elongation ranges from 1.7 to 3.2, with greater than 3 only being observed in samples 15 and 16 (Table 2). The most common elongation is around 2 to 2.5, and the greatest individual elongation may be up to 9 (Table 3, Figure 2). Zircon elongation-frequency curves are mostly unimodal (Figure 2), but that of samples 9 (granodiorite) and 16 (feldsparphyric rhyolite dyke) are bimodal. Sample 9 shows a primary maximum at 2.5 to 3 and a secondary maximum at 4. Sample 16 displays a primary maximum at 2 to 2.5 and a secondary maximum at 3.5. Crystal tuff (with hornblende) is found to have a maximum average elongation of 3.6, and the greatest individual elongation can be up to 9.5 (Table 3).

Size-frequencies (elongation-, length- and breadth-frequency) of all the samples are given in Ta-



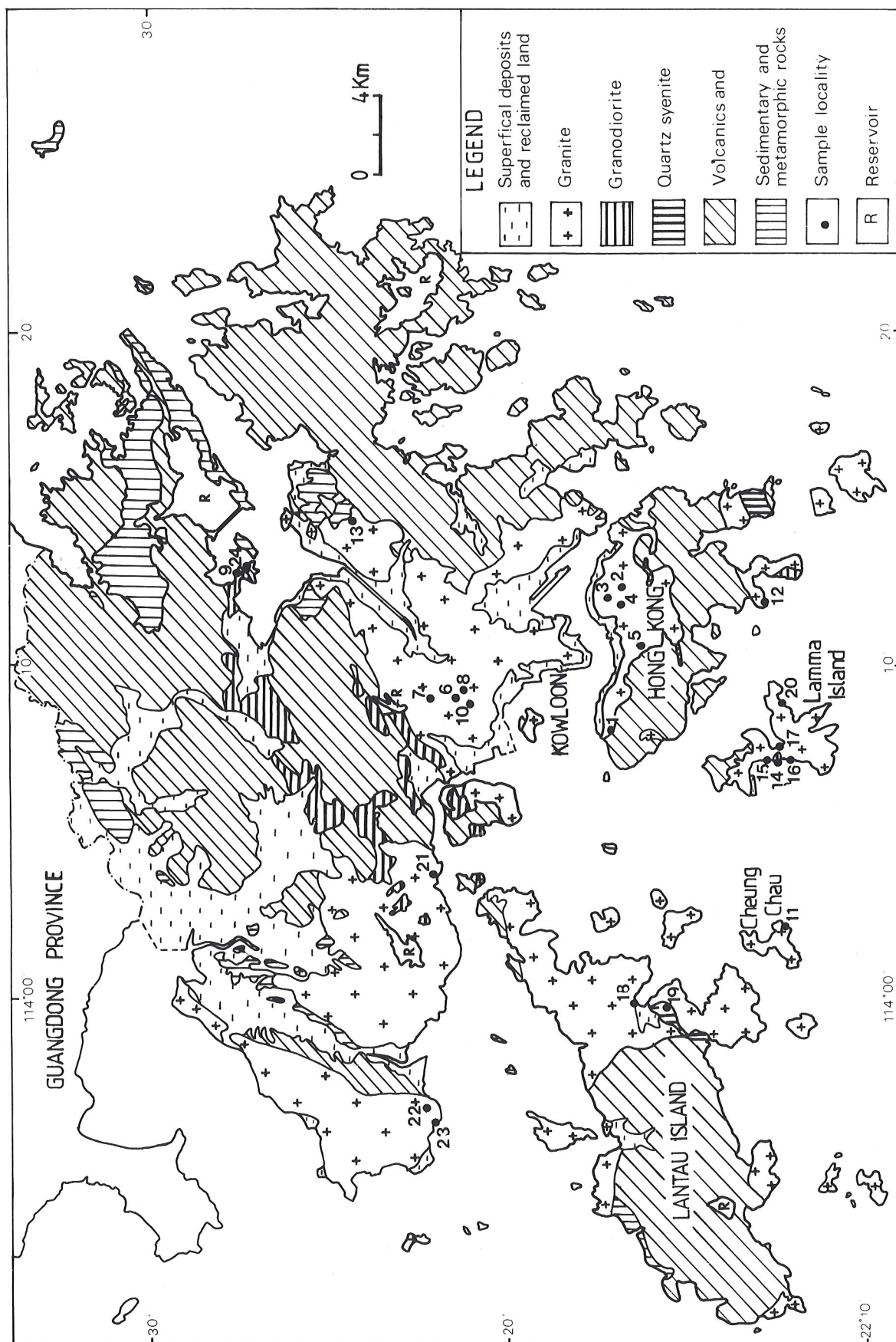


Figure 1 - Simplified geologic map showing sample localities

Table 1 - Abundance of zircon in granitoids and tuff

| Sample No. | Description of sample                   | Old name by Allen & Stephens (1971) | Pluton-based nomenclature**                        | Zircon content(kg/T) |
|------------|-----------------------------------------|-------------------------------------|----------------------------------------------------|----------------------|
| 1 (A)*     | Medium-grained granite                  | Hong Kong Granite                   | Lion Rock Suite, Subgroup III, Mount Bulter Pluton | 0.79                 |
| 2 (C)*     | Megacrystic fine-grained granite        | Hong Kong Granite                   | Lion Rock Suite, Subgroup III, Mount Bulter Pluton | 0.05                 |
| 3 (D)*     | Megacrystic fine-grained granite        | Hong Kong Granite                   | Lion Rock Suite, Subgroup III, Mount Bulter Pluton | 0.06                 |
| 4 (E)*     | Megacrystic fine-grained granite        | Hong Kong Granite                   | Lion Rock Suite, Subgroup III, Mount Bulter Pluton | 0.06                 |
| 5 (B)*     | Medium-grained granite                  | Hong Kong Granite                   | Lion Rock Suite, Subgroup III, Mount Bulter Pluton | 0.34                 |
| 6 (G)*     | Megacrystic fine-grained granite        | Needle Hill Granite                 | Lion Rock Suite, Subgroup II, Sha Tin Pluton       | 0.10                 |
| 7 (F)*     | Medium-grained granite                  | Cheung Chau Granite                 | Lion Rock Suite, Subgroup II, Sha Tin Pluton       | 3.50                 |
| 8 (I)*     | Coarse-grained granite                  | Sung Kung Granite                   | Lion Rock Suite, Subgroup II, Sha Tin Pluton       | 0.25                 |
| 9 (J)*     | Megacrystic coarse-grained granodiorite | Tai Po Granodiorite                 | lamma Suit, Tai Po Granodiorite                    | 0.35                 |
| 10 (H)*    | Megacrystic fine-grained granite        | Needle Hill Granite                 | Lion Rock Suite, Subgroup II, Sha Tin Pluton       | 0.12                 |
| 11         | Medium-grained granite                  | Cheung Chau Granite                 | Lion Rock Suite, Subgroup III, Chi Ma Wan Pluton   | 1.87                 |
| 12         | Medium-grained granite                  | Hong Kong Granite                   | Lion Rock Suite, Subgroup III, Stanley Pluton      | 0.38                 |
| 13         | Megacrystic fine-grained granite        | Ma On Shan Granite                  | Lion Rock Suite, Subgroup II, Sha Tin Pluton       | 0.80                 |
| 14         | Megacrystic coarse-grained granodiorite | Tai Po Granodiorite                 | lamma Suit, Tai Po Granodiorite                    | 163.80               |
| 15         | Coarse-grained granite                  | Sung Kung Granite                   | Lion Rock Suite, Subgroup III, South Lamma Pluton  | 18.59                |
| 16         | Feldsparphyric rhyolite dyke            | Feldspar porphyry                   |                                                    | 27.23                |
| 17         | Medium-grained granite                  | Cheung Chau Granite                 | Lion Rock Suite, Subgroup III, South Lamma Pluton  | 1.21                 |
| 18         | Fine-medium grained granite             | Granite                             | Lion Rock Suite, Subgroup II, Sung Kong Granite    | 5.39                 |
| 19         | Quartz syenite                          | Quartz monzonite                    | Lion Rock Suite, Subgroup II, quartz syenite       | 25.63                |
| 20         | Coarse-grained granite                  | Cheung Chau Granite                 | Lion Rock Suite, Subgroup III, South Lamma Pluton  | 47.21                |
| 21         | Medium-grained granite                  | Cheung Chau Granite                 | Lion Rock Suite, Subgroup I, Tai Lam Pluton        | 3.87                 |
| 22         | Coarse-grained granite                  | Cheung Chau Granite                 | Lion Rock Suite, Subgroup I, Tsing Shan Pluton     | 8.55                 |
| 23         | Fine-medium grained granite             | Cheung Chau Granite                 | Lion Rock Suite, Subgroup I, Tsi ng Shan Pluton    | 1.32                 |
| 24         | Coarse ash crystal tuff with hornblende |                                     |                                                    | 6.59                 |

\* Sample number used in earlier publication (Nau 1988)

\*\* Refer to Strange et al (1991), Sewell &amp; Langford (1991), and Sewell et al (1992)

bles 3, 4, 5 and Figures 2, 3. The most common length and breadth of zircon euhedra are around 0.15 mm and 0.075 mm respectively (Tables 4 and 5). Maximum length and breadth of the euhedra are 0.55 mm and 0.31 mm respectively (Table 2). If a zircon crystal with L/B ratio > 4 is considered a long prismatic zircon, then around 70% samples contain long prismatic zircons. Zircons with elongation equal to or greater than 9 are only observed in feldsparphyric rhyolite dyke and crystal tuff (with hornblende) but

not in plutonic rocks. In certain megacrystic fine-grained granites (samples 2, 4), the predominate zircon sizes are smaller in length and in breadth (around 0.05 mm and 0.025 mm respectively) as compared with other samples, and they also lack of further smaller size fractions (length and breadth) as compared with their own prevailing sizes (Tables 4, 5 and Figure 3). Obviously, zircon sizes (length and breadth) of sample 6 are much smaller (Tables 4, 5), but the result of twelve measurements is unreliable (Table 4).



Table 2 - Average size of zircon in granitoids and tuff

| Sample No. * | Description of sample                   | No. of Zircon measured | L/B  |      | Ratio |      | Length (mm) |       | Breadth (mm) |       |
|--------------|-----------------------------------------|------------------------|------|------|-------|------|-------------|-------|--------------|-------|
|              |                                         |                        | Ave. | Max. | Min.  | Ave. | Max.        | Min.  | Ave.         | Max.  |
| 1            | Medium-grained granite                  | 115                    | 2.2  | 3.5  | 1.3   | 0.33 | 0.550       | 0.160 | 0.150        | 0.310 |
| 2            | Megacrystic fine-grained granite        | 42                     | 2.2  | 3.3  | 1.0   | 0.05 | 0.190       | 0.015 | 0.023        | 0.065 |
| 3            | Megacrystic fine-grained granite        | 100                    | 2.2  | 5.9  | 1.0   | 0.14 | 0.500       | 0.070 | 0.066        | 0.125 |
| 4            | Megacrystic fine-grained granite        | 67                     | 2.1  | 6.4  | 1.0   | 0.04 | 0.200       | 0.008 | 0.019        | 0.100 |
| 5            | Medium-grained granite                  | 277                    | 2.2  | 4.1  | 1.1   | 0.16 | 0.310       | 0.070 | 0.075        | 0.150 |
| 6            | Megacrystic fine-grained granite        | 12                     | 2.1  | 5.6  | 1.0   | 0.01 | 0.028       | 0.005 | 0.010        | 0.010 |
| 7            | Medium-grained granite                  | 210                    | 2.6  | 6.7  | 1.3   | 0.17 | 0.500       | 0.075 | 0.067        | 0.300 |
| 8            | Coarse-grained granite                  | 111                    | 1.9  | 4.6  | 1.2   | 0.15 | 0.300       | 0.075 | 0.085        | 0.175 |
| 9            | Megacrystic coarse-grained granodiorite | 214                    | 2.8  | 6.0  | 1.3   | 0.22 | 0.500       | 0.075 | 0.080        | 0.220 |
| 10           | Megacrystic fine-grained granite        | 60                     | 2.2  | 3.6  | 1.3   | 0.15 | 0.250       | 0.075 | 0.070        | 0.120 |
| 11           | Medium-grained granite                  | 160                    | 2.0  | 3.2  | 1.3   | 0.16 | 0.300       | 0.080 | 0.090        | 0.150 |
| 12           | Medium-grained granite                  | 120                    | 2.0  | 4.3  | 1.0   | 0.12 | 0.280       | 0.070 | 0.060        | 0.110 |
| 13           | Megacrystic fine-grained granite        | 117                    | 1.7  | 2.8  | 1.0   | 0.11 | 0.180       | 0.060 | 0.070        | 0.120 |
| 14           | Megacrystic coarse-grained granodiorite | 113                    | 1.9  | 6.6  | 1.2   | 0.12 | 0.480       | 0.060 | 0.070        | 0.140 |
| 15           | Coarse-grained granite                  | 113                    | 3.2  | 7.6  | 1.5   | 0.22 | 0.550       | 0.100 | 0.069        | 0.140 |
| 16           | Feldsparphyric rhyolite dyke            | 124                    | 3.2  | 9.0  | 1.0   | 0.24 | 0.500       | 0.080 | 0.075        | 0.180 |
| 17           | Medium-grained granite                  | 123                    | 1.9  | 3.1  | 1.1   | 0.18 | 0.500       | 0.070 | 0.100        | 0.200 |
| 18           | Fine-medium grained granite             | 200                    | 2.3  | 4.1  | 1.3   | 0.15 | 0.300       | 0.060 | 0.070        | 0.140 |
| 19           | Quartz syenite                          | 105                    | 2.7  | 5.7  | 1.1   | 0.20 | 0.400       | 0.100 | 0.080        | 0.140 |
| 20           | Coarse-grained granite                  | 124                    | 2.9  | 8.9  | 1.2   | 0.23 | 0.480       | 0.100 | 0.080        | 0.140 |
| 21           | Medium-grained granite                  | 121                    | 2.4  | 5.6  | 1.0   | 0.18 | 0.450       | 0.090 | 0.080        | 0.250 |
| 22           | Coarse-grained granite                  | 347                    | 2.1  | 8.3  | 1.0   | 0.12 | 0.350       | 0.020 | 0.060        | 0.140 |
| 23           | Fine-medium grained granite             | 359                    | 2.2  | 5.3  | 1.0   | 0.14 | 0.290       | 0.030 | 0.070        | 0.150 |
| 24           | Coarse ash crystal tuff with hornblende | 57                     | 3.6  | 9.2  | 1.1   | 0.27 | 0.500       | 0.100 | 0.090        | 0.130 |

### Typologic Distribution of Zircon Populations

On the basis of the study of zircon morphology or population type (the arrangement of prismatic and pyramidal crystal faces of zircon crystal), Pupin (1980) has put forward a zircon typologic classification and developed a quantitative analytical technique. He has also proposed a petrogenetical classification. Zircon typologic classification derived by Pupin is shown in Figure 4, where Indice T (temperature indice) corresponds to temperature scale from 550°C

to 900°C and Indice A (Al/alkaline indice) indicates the chemical characteristics (hyperaluminous or hypoalkaline to hyperalkaline or hypoaluminous) of crystallization media.

In this paper, zircon populations (morphologic types) of each sample are determined by examination of 100 to 200 zircon crystals (both transparent and translucent crystals) or even more, but may be less than 100 if zircon crystals in a sample are rare. The results of all the samples are given in Table 6 and

Table 3 - Zircon elongation-frequency (L/B ratio)

| Sample No. * | L/B ratio |      |      |      |      |      |      |     |     |     |     |     |     |     |     |     |     |     |
|--------------|-----------|------|------|------|------|------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|              | 1.0       | 1.5  | 2.0  | 2.5  | 3.0  | 3.5  | 4.0  | 4.5 | 5.0 | 5.5 | 6.0 | 6.5 | 7.0 | 7.5 | 8.0 | 8.5 | 9.0 | 9.5 |
| 1            |           | 3.5  | 40.4 | 42.1 | 11.4 | 3.5  |      |     |     |     |     |     |     |     |     |     |     |     |
| 2            | 4.8       | 14.2 | 26.2 | 38.1 | 9.5  | 9.5  |      |     |     |     |     |     |     |     |     |     |     |     |
| 3            | 1.0       | 9.0  | 40.0 | 33.0 | 10.0 | 2.0  | 3.0  |     | 1.0 |     | 1.0 |     |     |     |     |     |     |     |
| 4            | 3.0       | 14.9 | 41.8 | 23.9 | 10.4 | 1.5  | 1.5  |     |     |     | 1.5 |     |     |     |     |     |     |     |
| 5            |           | 5.8  | 38.0 | 37.3 | 14.9 | 2.2  | 1.4  | 0.4 |     |     |     |     |     |     |     |     |     |     |
| 6            |           | 8.3  | 8.3  | 58.3 | 16.7 |      |      |     |     |     | 8.3 |     |     |     |     |     |     |     |
| 7            |           | 1.9  | 30.0 | 25.8 | 21.5 | 8.1  | 5.7  | 3.3 | 1.9 | 1.0 |     | 0.5 | 0.5 |     |     |     |     |     |
| 8            |           | 33.6 | 39.0 | 17.3 | 3.6  | 1.8  | 2.7  | 0.9 | 0.9 |     |     |     |     |     |     |     |     |     |
| 9            |           | 1.4  | 19.2 | 24.4 | 24.4 | 14.5 | 18.8 | 6.1 |     | 0.9 | 0.9 |     |     |     |     |     |     |     |
| 10           |           | 11.9 | 32.2 | 33.9 | 13.6 | 6.8  | 1.7  |     |     |     |     |     |     |     |     |     |     |     |
| 11           |           | 12.0 | 58.6 | 22.0 | 6.3  | 1.3  |      |     |     |     |     |     |     |     |     |     |     |     |
| 12           | 0.83      | 16.7 | 46.7 | 25.0 | 8.3  |      | 1.7  | 0.8 |     |     |     |     |     |     |     |     |     |     |
| 13           | 0.8       | 47.4 | 40.5 | 9.5  | 1.7  |      |      |     |     |     |     |     |     |     |     |     |     |     |
| 14           |           | 4.4  | 8.0  | 31.0 | 32.7 | 13.3 | 4.4  | 1.8 | 0.9 |     | 0.9 | 1.8 | 0.9 |     |     |     |     |     |
| 15           |           | 0.9  | 3.6  | 20.5 | 26.8 | 24.0 | 11.6 | 2.7 | 4.5 | 0.9 | 0.9 | 0.9 | 1.8 |     | 0.9 |     |     |     |
| 16           | 0.8       |      | 18.5 | 16.9 | 12.1 | 27.4 | 15.3 | 2.4 | 0.8 | 3.2 | 0.8 | 0.8 |     |     |     | 0.8 |     |     |
| 17           |           | 22.0 | 38.5 | 32.8 | 5.7  | 0.8  |      |     |     |     |     |     |     |     |     |     |     |     |
| 18           |           | 2.5  | 33.2 | 37.2 | 19.0 | 5.0  | 2.0  | 1.0 |     |     |     |     |     |     |     |     |     |     |
| 19           |           | 11.5 | 6.7  | 28.8 | 24.0 | 13.0 | 10.6 | 1.9 | 1.0 | 1.0 |     |     |     |     |     |     |     |     |
| 20           |           | 2.7  | 5.5  | 29.0 | 30.0 | 17.3 | 10.9 | 1.8 | 0.9 | 0.9 |     |     |     |     | 0.9 |     |     |     |
| 21           | 2.5       | 6.7  | 21.7 | 28.3 | 20.8 | 10.0 | 8.3  | 0.8 |     |     | 0.8 |     |     |     |     |     |     | 1.8 |
| 22           | 4.0       | 22.0 | 27.8 | 28.0 | 8.6  | 4.9  | 2.0  |     | 1.1 |     | 0.6 |     | 0.3 |     |     | 0.6 |     |     |
| 23           | 2.8       | 17.5 | 29.2 | 27.9 | 13.1 | 3.3  | 3.6  | 0.8 | 1.1 | 0.6 |     |     |     |     |     |     |     |     |
| 24           |           | 5.4  | 3.6  | 14.3 | 28.6 | 19.6 | 16.1 | 3.6 | 5.4 |     | 1.8 |     |     |     |     |     |     | 1.8 |

\* Sample descriptions see Table 1

Figure 5. Based on the analytical techniques described by Pupin (1980), mean temperature indice (IT), mean Al/alkaline indice (IA), slope ( $\alpha$ ) and corresponding temperatures (T) of each sample are found and shown in Table 6 and Figure 6. As a whole, the zircon observed are mainly types G, P<sub>1-5</sub>, D, S<sub>23-25</sub> and J<sub>3-5</sub>. In addition, a few zircon crystals of types D, J<sub>4</sub> and S<sub>24</sub> with pyramid (301) can be found in samples 7 and 9.

#### Typologic Distribution of Transparent and Translucent Zircon Populations

The transparent and translucent (including subtranslucent) zircon crystals from three samples (21, 22, 23) have been examined separately to determine their typologic distributions. The results are given in Figure 7.

For transparent crystals, the zircon observed are mainly types P<sub>5</sub> and D, but without any types G

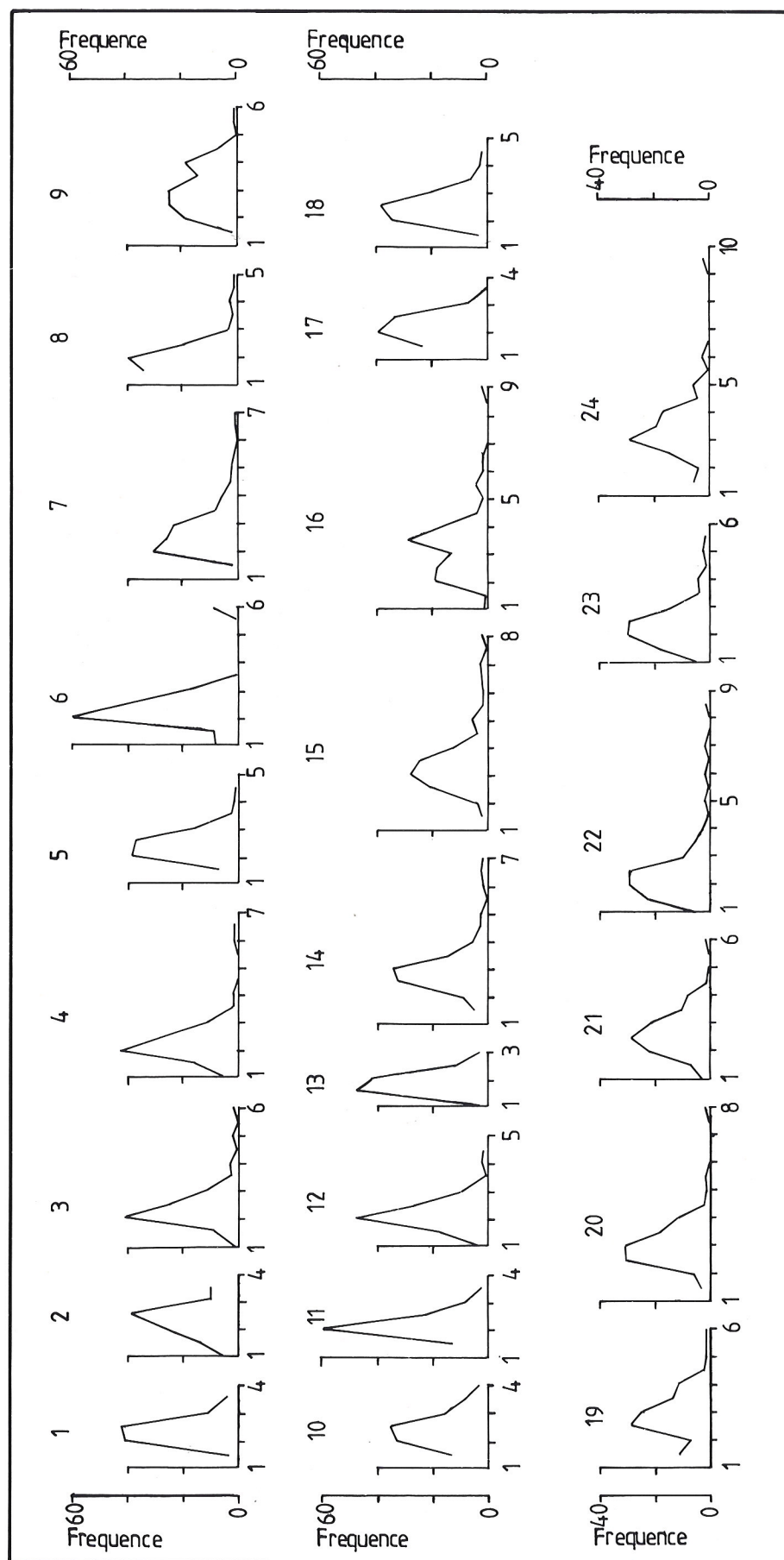


Figure 2 - Zircon elongation-frequency curves



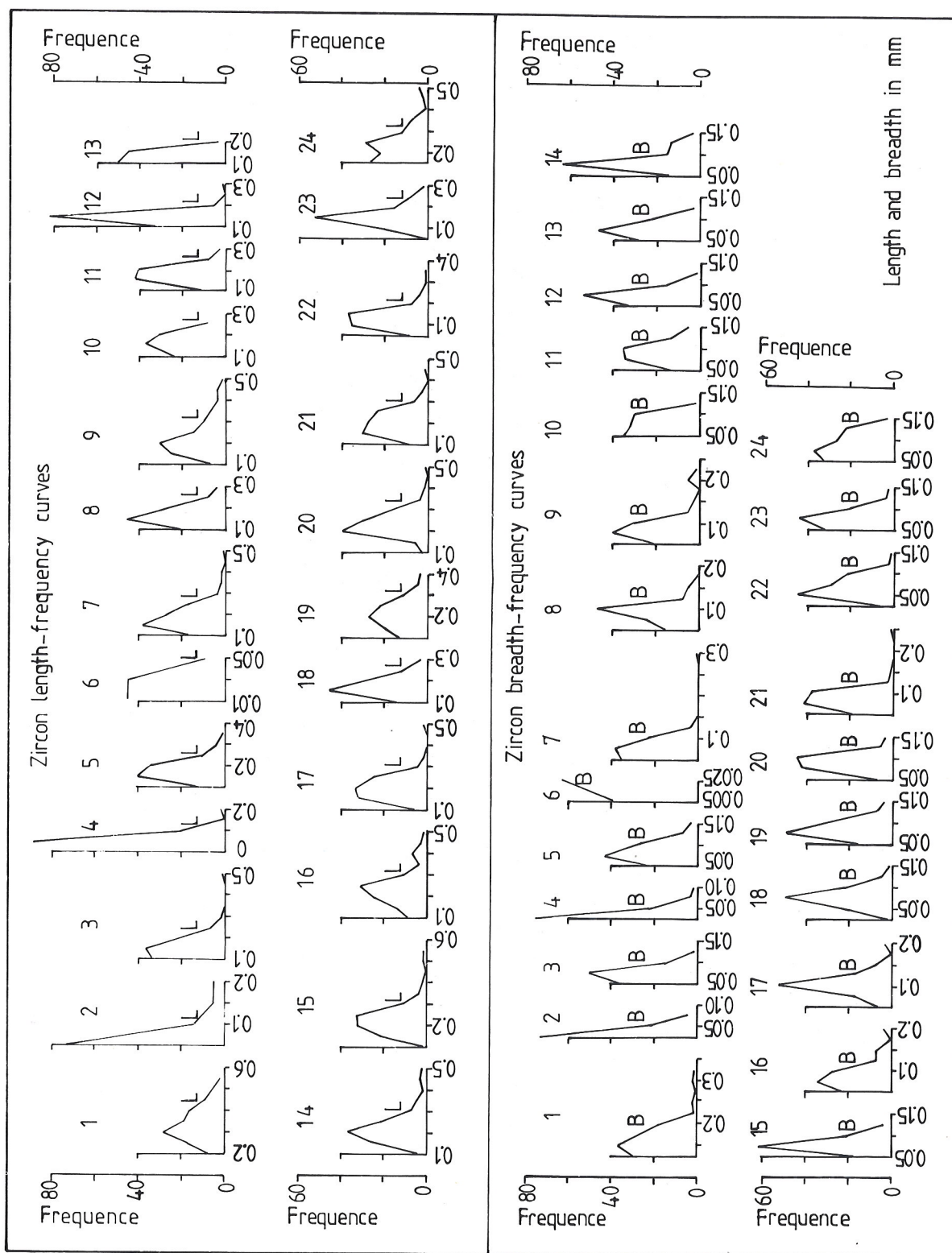


Figure 3 - Zircon length- and breadth-frequency curves

and  $P_1$ . All three samples have high IT (707-737) indicating high crystallization temperatures (850°-870°).

For translucent crystals, types  $P_1$  and G are the main types observed in samples 21 and 22, while the main zircon type of sample 23 is type  $P_5$ . Two samples have low IT indicating relatively low crys-

tallization temperatures (710°-725°) but one sample has medium IT marking rather high crystallization temperature (800°).

The similar IA for transparent and translucent zircons indicate that they are from crystallization media having similar chemical characteristics. The variation in IT indicates that the zircon crystallization

Table 4 - Zircon length-frequency

| Sample No. * | Length (mm) |       |       |       |       |       |       |       |       |       |       |       |       |
|--------------|-------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|              | 0.010       | 0.025 | 0.050 | 0.100 | 0.150 | 0.200 | 0.250 | 0.300 | 0.350 | 0.400 | 0.450 | 0.500 | 0.550 |
| 1            |             |       |       |       |       | 6.1   | 16.7  | 27.2  | 18.4  | 15.8  | 8.8   | 5.3   | 1.8   |
| 2            |             |       | 76.2  | 14.3  | 4.8   | 4.8   |       |       |       |       |       |       |       |
| 3            |             |       |       | 33.3  | 36.4  | 22.2  | 6.0   | 1.0   |       |       |       | 1.0   |       |
| 4            |             |       | 79.1  | 19.4  |       | 1.5   |       |       |       |       |       |       |       |
| 5            |             |       |       | 11.9  | 40.2  | 34.4  | 9.8   | 3.2   | 0.36  |       |       |       |       |
| 6            | 45.5        | 45.5  | 9.0   |       |       |       |       |       |       |       |       |       |       |
| 7            |             |       |       | 13.4  | 38.3  | 27.3  | 14.8  | 3.3   | 1.4   | 0.9   |       | 0.48  |       |
| 8            |             |       |       | 17.3  | 45.4  | 26.4  | 8.1   | 2.7   |       |       |       |       |       |
| 9            |             |       |       | 5.7   | 24.8  | 30.1  | 14.1  | 10.3  | 6.6   | 3.8   | 3.7   | 1.0   |       |
| 10           |             |       |       | 23.7  | 37.3  | 30.5  | 8.5   |       |       |       |       |       |       |
| 11           |             |       |       | 7.5   | 42.0  | 40.8  | 7.6   | 1.9   |       |       |       |       |       |
| 12           |             |       |       | 25.8  | 67.5  | 5.0   |       | 1.7   |       |       |       |       |       |
| 13           |             |       |       | 50.9  | 45.7  | 3.4   |       |       |       |       |       |       |       |
| 14           |             |       |       | 1.8   | 24.8  | 37.1  | 20.3  | 7.0   | 3.5   | 0.9   | 2.6   | 1.8   |       |
| 15           |             |       |       | 0.9   | 21.4  | 30.4  | 31.3  | 9.8   | 2.7   | 1.8   |       | 0.9   | 0.9   |
| 16           |             |       |       | 8.1   | 13.7  | 24.2  | 31.4  | 9.7   | 3.2   | 6.5   | 2.4   | 0.8   |       |
| 17           |             |       |       | 4.9   | 31.7  | 32.6  | 25.2  | 4.0   | 0.8   |       |       | 0.8   |       |
| 18           |             |       |       | 10.0  | 46.2  | 30.1  | 12.0  | 1.5   |       |       |       |       |       |
| 19           |             |       |       | 12.5  | 20.2  | 26.8  | 21.7  | 11.6  | 3.9   | 2.9   |       |       |       |
| 20           |             |       |       | 2.7   | 6.0   | 40.5  | 29.7  | 16.0  | 2.7   | 0.9   |       | 0.9   |       |
| 21           |             |       |       | 8.3   | 30.5  | 28.0  | 23.2  | 6.5   | 2.4   |       | 0.8   |       |       |
| 22           |             |       | 9.3   | 34.7  | 36.1  | 6.9   | 3.5   | 0.9   | 0.9   |       |       |       |       |
| 23           |             |       | 0.8   | 23.1  | 53.3  | 15.0  | 6.9   | 0.3   |       |       |       |       |       |
| 24           |             |       |       |       | 26.8  | 21.4  | 28.6  | 10.7  | 7.1   |       | 1.8   | 3.6   |       |

\* Sample descriptions see Table 1

cycle of the three samples may be of long duration covering the entire magmatic stage with transparent zircons crystallizing earlier than the translucent and subtranslucent ones.

#### Other Accessory Heavy Minerals

Heavy mineral assemblages and weight percentages of the minerals with  $SG > 3.3$  of the twenty-four samples are given in Table 7. Magnetite, ilmenite and zircon are the most common minerals. Two thirds of the sample have magnetite more than ilmenite and only one third has ilmenite more than magnetite.

Sample 6 contains no magnetite and ilmenite, and sample 22 contains no ilmenite. Only zircon is common in all the samples. About half of the samples contain zircon crystals more than 30% (by weight).

Monazite, xenotime, thorite and limonite (weathering mineral) are the next commonly occurring minerals in about half of the samples.

Pneumatolytic minerals (wolframite, cassiterite, molybdenite, tourmaline) are found to occur in eleven samples (1, 3, 6, 7, 8, 10, 13, 15, 16, 22, 23). Wolframite is the more common pneumatolytic mineral in megacrystic fine-grained (sometimes fine-



Table 5 - Zircon breadth-frequency

| Sample No. * | Breadth (mm) |       |       |       |       |       |       |       |       |       |       |       |       |       |
|--------------|--------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|              | 0.005        | 0.025 | 0.050 | 0.075 | 0.100 | 0.125 | 0.150 | 0.175 | 0.200 | 0.225 | 0.250 | 0.275 | 0.300 | 0.325 |
| 1            |              |       |       |       |       | 28.0  | 36.0  | 12.3  | 18.4  | 0.9   | 1.80  |       | 1.80  | 0.9   |
| 2            |              | 73.2  | 22.0  | 4.8   |       |       |       |       |       |       |       |       |       |       |
| 3            |              |       | 34.3  | 50.5  | 14.1  | 1.1   |       |       |       |       |       |       |       |       |
| 4            |              | 74.6  | 20.9  | 3.0   | 1.5   |       |       |       |       |       |       |       |       |       |
| 5            |              |       | 19.9  | 43.4  | 27.2  | 6.9   | 2.5   |       |       |       |       |       |       |       |
| 6            | 36.4         | 63.6  |       |       |       |       |       |       |       |       |       |       |       |       |
| 7            |              |       | 35.4  | 38.3  | 23.0  | 3.3   |       |       |       |       |       |       | 0.5   |       |
| 8            |              |       | 14.5  | 24.5  | 47.3  | 7.3   | 5.5   | 0.9   |       |       |       |       |       |       |
| 9            |              |       | 18.8  | 40.3  | 29.6  | 5.2   | 2.8   |       | 5.2   | 0.5   |       |       |       |       |
| 10           |              |       | 35.6  | 32.2  | 30.5  | 1.7   |       |       |       |       |       |       |       |       |
| 11           |              |       | 12.0  | 34.6  | 35.2  | 13.2  | 5.0   |       |       |       |       |       |       |       |
| 12           |              |       | 29.2  | 55.0  | 15.0  | 0.8   |       |       |       |       |       |       |       |       |
| 13           |              |       | 25.0  | 48.3  | 23.3  | 3.4   |       |       |       |       |       |       |       |       |
| 14           |              |       | 6.2   | 63.7  | 15.0  | 13.2  | 1.8   |       |       |       |       |       |       |       |
| 15           |              |       | 15.2  | 61.6  | 19.6  | 3.6   |       |       |       |       |       |       |       |       |
| 16           |              |       | 21.8  | 34.5  | 27.4  | 6.5   | 6.5   |       | 3.2   |       |       |       |       |       |
| 17           |              |       | 4.9   | 17.1  | 52.0  | 16.3  | 6.5   |       | 3.3   |       |       |       |       |       |
| 18           |              | 0.5   | 20.6  | 51.3  | 21.6  | 5.0   | 1.0   |       |       |       |       |       |       |       |
| 19           |              |       | 10.6  | 49.0  | 28.8  | 7.7   | 3.8   |       |       |       |       |       |       |       |
| 20           |              |       | 3.6   | 41.8  | 44.5  | 6.4   | 3.6   |       |       |       |       |       |       |       |
| 21           |              |       | 14.9  | 41.3  | 38.0  | 2.5   | 1.6   |       |       |       | 1.6   |       |       |       |
| 22           |              | 1.7   | 45.1  | 28.0  | 21.7  |       |       |       |       |       |       |       |       |       |
| 23           |              |       | 30.6  | 43.7  | 19.8  | 3.6   | 2.2   |       |       |       |       |       |       |       |
| 24           |              |       | 31.6  | 36.8  | 15.8  | 12.3  | 3.5   |       |       |       |       |       |       |       |

\* Sample descriptions see Table 1

to medium-grained) granites and also feldsparphyric rhyolite dyke. It appears mostly with cassiterite (samples 6, 10 and 13) or rarely with molybdenite (sample 23). Tourmaline, pyrite and hematite are scarce minerals.

Epidote, being mostly a secondary mineral, not detected in granitic rocks, is mainly observed in granodiorite, syenite and crystal tuff (with hornblende).

Garnet (almandine, 12.7% by weight) is only observed in sample 17 (medium-grained granite). However, one grain of garnet is also found in sample 14 (granodiorite). The presence of garnet may probably be due to contamination of magma by assimilation.

Samples having similar heavy mineral assemblages are not common. Samples 1 and 5 have similar magnetite-ilmenite-zircon-monazite-xenotime as-



semblages, and samples 7, 15, and 19 show similar magnetite-ilmenite-zircon assemblages.

### Discussion

According to the measurements of zircon size of the granitoid samples, zircon sizes are fairly regular. The most common length and breadth of zircon crystals are around 0.15 mm and 0.075 mm respectively, and the most common elongation is around 2 or 2.5. However, a few samples (2, 4 and probably 6) have smaller zircon sizes in length and in breadth around 0.05 mm and 0.025 mm respectively.

There is a slight difference in zircon size between granitoids and crystal tuff (with hornblende) although there is only one sample of crystal tuff. Average zircon elongation of 3.6 of crystal tuff (with hornblende) is the maximum as compared with that of granitoids.

From the distribution of mean points (IA, IT) of zircon populations and zircon population indices (Figure 6, Table 6), the narrow range of IA from 657 to 700 (Table 6) of the nineteen granitic samples indicates that the crystallization media for granitic rocks have similar chemical characteristics. According to the petrogenetic classification proposed by Pupin (1980), the results of the granitic rocks concerned fall into the Pupin's category of alkaline series granites of mainly mantle origin (however, no alkaline minerals can be observed in the rocks). Alkalinity ratios (see Appendix 1) of forty-seven granitic samples, ranging from 1.99 to 4.69 with an average of 3.15, indicate that the rocks are of subalkaline to weak alkaline series (data of chemical analyses refer to Addison, 1986, Strange and Shaw, 1986, Langford, Lai, Arthurton and Shaw, 1989, and Sewell, Derbyshire, Langford and Strange, 1992).

Indices IT of the above granitic rocks have a wide range varying from 283 to 765 (645°-880°). Thirteen of the nineteen granitic samples (1, 2, 3, 4, 5, 7, 8, 12, 15, 20, 21, 22, and 23) have high IT (574-765), corresponding to medium to high crystallization temperatures (785°-880°), and medium slope. These samples, with a little variation within the zircon population, have zircon crystals mainly of types P<sub>2</sub> and D (early zircon). Only a few samples contain pneumatolytic minerals (Table 7). It is suspected that the granitic rocks in question are of deeper source series formed in much greater depth than the granitic rocks represented by the other 6 samples (Nos. 6, 10, 11, 13, 17 and 18) mentioned in the following paragraph, and had been partly subjected to very slight pneumatolytic processes. Besides, two of these samples (Nos. 2 and 4 of megacrystic fine-grained granite) as mentioned above have smaller zircon sizes. If we accept the statement that elongation trends are interpreted to be a function of different physiochemical conditions during crystallization (Spotts, 1962), then the granites represented by samples 2 and 4 may prob-

ably originate from a different crystallization condition.

Six of the nineteen granitic samples (6, 10, 11, 13, 17, and 18) as shown in Figure 6 have low IT, ranging from 283 to 470, corresponding to low crystallization temperatures (645°-735°), and high slopes. Zircon typologic distributions of these samples are localized (Figure 5). Zircon types observed are mainly types P<sub>1</sub> and G (late zircon). Three (samples 6, 10, 13) of the six samples yield cassiterite and wolframite, and sample 17 contains almandine garnet (Table 7). It seems that these granitic rocks concerned may be formed near the roof of relative shallow source at the end of differentiation of magma and had subjected to pneumatolytic processes, and part of them may subjected to contamination by assimilation.

Two samples (9 and 14) collected from the granodiorite do not have similar typologic distributions of zircon populations (Figure 5). For sample 9, IA=546, IT=730,  $\alpha = 42^\circ$ ; and for sample 14, IA=664, IT=699,  $\alpha = 69^\circ$ . Obviously, sample 14 has similarities in IA, IT and  $\alpha$  with those of granitic samples (of deeper source series), but sample 9 is not. Moreover, differences between the two samples can also be found in heavy mineral assemblages (sample 9 has more magnetite but less zircon and ilmenite as compared with sample 14) and in elongation-frequency curves (frequency curve of sample 9 is bimodal and that of sample 14 is unimodal). As judged from Figures 4 and 6, chemical characteristics of granodiorite may vary from calc-alkaline to subalkaline. Alkalinity ratios of nine granodiorite samples, ranging from 1.82 to 2.62 with an average of 2.08, indicate that the rocks belong to calc-alkaline series (data of chemical analyses refer to Addison, 1986; Langford, Lai, Arthurton and Shaw, 1989; Sewell, Derbyshire, Langford and Strange, 1992). In addition, zircon typologic distribution (Figure 5) and zircon indices (IA, IT and  $\alpha$ ) of sample 9 are fairly similar to that of sample 24 (crystal tuff with hornblende), but they do not have similar heavy mineral assemblages. It is possible that there may have been a close relationship between the magmatic sources producing crystal tuff with hornblende and granodiorite. However, as there are only two granodiorite samples and one crystal tuff sample, reliable conclusions can not be made.

Typologic distribution of samples 19 (quartz syenite) is similar to that of plutonic granitic samples having type D as the main zircon type but with type J<sub>3</sub> the secondary type (for plutonic granitic samples, type J is usually not the secondary type). This sample yields pneumatolytic minerals in scarce amount. Alkalinity ratios of quartz syenites (nine samples), ranging from 1.78 to 2.56 with an average of 2.17, show that the rocks may be of calc-alkaline series (data of chemical analyses refer to Addison, 1986, Strange and Shaw, 1986, and Sewell, Derbyshire, Langford and Strange, 1992). According to the distribution of mean points

|   |              | Hyperaluminous /<br>hypoalkaline |                     |                     | Calc-Alkaline       |                     | Sub-<br>alkaline    | Alkaline                                         | Theoretical        |            |   |
|---|--------------|----------------------------------|---------------------|---------------------|---------------------|---------------------|---------------------|--------------------------------------------------|--------------------|------------|---|
|   |              | P<br>(211)                       | Y<br>(101)<<(211)   | R<br>(101)<(211)    | A<br>(101)=(211)    | M<br>(101)>(211)    | I<br>(101)>>(211)   | D<br>(101)                                       | E<br>(101)         | S<br>(301) |   |
| P | Prism<br>0   | <br>B                            | <br>AB <sub>1</sub> | <br>AB <sub>2</sub> | <br>AB <sub>3</sub> | <br>AB <sub>4</sub> | <br>AB <sub>5</sub> | <br>A                                            | <br>C              | 100        | I |
| R | (110)        | <br>H                            | <br>L <sub>1</sub>  | <br>L <sub>2</sub>  | <br>L <sub>3</sub>  | <br>L <sub>4</sub>  | <br>L <sub>5</sub>  | <br>G <sub>1</sub> G <sub>2</sub> G <sub>3</sub> | <br>I              | 200        | N |
| I | (100)<<(110) | <br>Q <sub>1</sub>               | <br>S <sub>1</sub>  | <br>S <sub>2</sub>  | <br>S <sub>3</sub>  | <br>S <sub>4</sub>  | <br>S <sub>5</sub>  | <br>P <sub>1</sub>                               | <br>R <sub>1</sub> | 300        | D |
| S | (100)<(110)  | <br>Q <sub>2</sub>               | <br>S <sub>6</sub>  | <br>S <sub>7</sub>  | <br>S <sub>8</sub>  | <br>S <sub>9</sub>  | <br>S <sub>10</sub> | <br>P <sub>2</sub>                               | <br>R <sub>2</sub> | 400        | I |
| M | (100)=(110)  | <br>Q <sub>3</sub>               | <br>S <sub>11</sub> | <br>S <sub>12</sub> | <br>S <sub>13</sub> | <br>S <sub>14</sub> | <br>S <sub>15</sub> | <br>P <sub>3</sub>                               | <br>R <sub>3</sub> | 500        | C |
| E | (100)>(110)  | <br>Q <sub>4</sub>               | <br>S <sub>16</sub> | <br>S <sub>17</sub> | <br>S <sub>18</sub> | <br>S <sub>19</sub> | <br>S <sub>20</sub> | <br>P <sub>4</sub>                               | <br>R <sub>4</sub> | 600        | E |
| S | (100)>>(110) | <br>Q <sub>5</sub>               | <br>S <sub>21</sub> | <br>S <sub>22</sub> | <br>S <sub>23</sub> | <br>S <sub>24</sub> | <br>S <sub>25</sub> | <br>P <sub>5</sub>                               | <br>R <sub>5</sub> | 700        |   |
|   | (100)        | <br>E                            | <br>J <sub>1</sub>  | <br>J <sub>2</sub>  | <br>J <sub>3</sub>  | <br>J <sub>4</sub>  | <br>J <sub>5</sub>  | <br>D                                            | <br>F              | 800        | T |
|   |              | 100<br>I                         | 200<br>N            | 300<br>D            | 400<br>I            | 500<br>C            | 600<br>E            | 700                                              | 800<br>A           |            |   |

± 50°  
▼  
500° C  
550° C

600° C  
650° C  
700° C  
750° C  
800° C  
850° C  
900° C

Figure 4 - Zircon typologic classification and corresponding geothermometric scale (after Pupin, 1980)

(IA, IT), quartz syenite concerned is tentatively attributed to calc-alkaline (or subalkaline) series granites of crustal + mantle origin (refer to Pupin, 1980). This rock type had subjected to very slight pneumatolytic process.

Zircon typologic distribution of sample 16 (feldsparphyric rhyolite) is similar to that of sample 19 with type D to be the main zircon type and type J<sub>5</sub> being the secondary type (Figure 5). Indices IA and IT are similar to that of granitic samples (of deeper source series) but slope ( $\alpha = 27^\circ$ ) is low (Table 6). Alkalinity ratio is found to be 2.7 indicating an subalkaline series (data of chemical analyses referred to Strange and Shaw, 1986). This sample had subjected to pneumatolytic processes and contains pneumatolytic minerals wolframite and tourmaline (Table 7). According to the distribution of mean Points (IA, IT) and the similarity of zircon typologic distribution with sample 19, the rock is tentatively included into calc-alkaline (or subalkaline) series granites of crustal + mantle origin.

Zircon typologic distribution and zircon indices (IA, IT,  $\alpha$ ) of sample 24 (crystal tuff with hornblende) are quite similar to samples 9 and 19. Zircon crystals of this sample are mainly types S<sub>23-25</sub> and J<sub>3</sub>, J<sub>5</sub> (Figure 5). The sample yields much more zircon and less magnetite and ilmenite (Table 7). In consideration of the mean points (IA, IT) of zircon populations and typologic distribution, the rock type can be tentatively classified to calc-alkaline (or subalkaline) series granites of crustal + mantle origin.

### Conclusions

Some conclusions can be made as follows:

1. The most common length and breadth of zircon crystals are 0.15 mm and 0.075 mm respectively. The maximum length and breadth of the euhedra are found to be 0.55 mm and 0.31 mm respectively. Average elongation (L/B ratio) of granitoid rocks vary from 1.7 to 3.2. The most common elongation is around 2 to 2.5. The greatest elonga-

Table 6 - Zircon population types (in percentage) and zircon population indices

| Type        | Sample |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|-------------|--------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|             | 1      | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   | 14   | 15   | 16   | 17   | 18   | 19   | 20   | 21   | 22   | 23   | 24   |
| G           | 1.5    | 2.7  | 7.1  | 6.1  | 3.9  | 25.0 | 0.3  | 2.9  |      | 71.4 | 38.2 |      | 45.6 | 7.6  |      |      | 56.0 | 11.0 |      |      | 15.6 | 3.6  |      |      |
| P1          | 0.5    | 2.7  | 12.9 | 1.2  | 9.7  | 31.3 | 0.8  | 2.9  |      | 8.6  | 25.7 | 1.8  | 70.2 | 2.3  | 0.7  |      | 2    | 21.0 | 0.9  |      |      | 9.2  | 16.8 | 1.2  |
| P2          | 2.5    | 9.6  | 5.2  | 2.4  | 4.2  | 6.3  | 1.5  | 0.6  |      | 3.8  | 15.8 | 0.6  | 7.6  |      | 0.7  |      | 4.8  | 10.5 |      | 1.1  | 2.0  | 7.0  | 0.6  |      |
| P3          | 8.5    | 2.7  | 3.9  | 22.0 | 7.9  | 6.3  | 3.6  | 7.5  | 2.2  | 2.9  | 11.8 | 4.7  | 5.9  | 4.1  | 0.7  |      | 4.8  | 18.0 |      |      | 6.7  | 10.9 | 13.1 |      |
| P4          | 20.6   | 32.9 | 12.9 | 7.3  | 24.2 | 6.3  | 10.5 | 9.8  | 3.9  | 5.7  | 5.9  | 17.1 | 10.5 | 2.3  | 1.4  |      | 0.8  | 13.0 | 1.3  | 2.8  | 12.5 | 10.9 | 17.7 |      |
| P5          | 31.7   | 35.6 | 37.4 | 33.0 | 33.9 | 18.8 | 32.4 | 36.7 | 13.4 | 3.8  | 2.0  | 44.1 | 14.0 | 16.4 | 18.9 | 9.5  | 4.8  | 12.5 | 8.1  | 47.8 | 22.8 | 28.9 | 39.3 | 11.9 |
| D           | 13.6   | 12.3 | 20.0 | 18.3 | 2.7  |      | 33.2 | 28.9 | 9.8  | 1.9  | 0.7  | 14.7 | 1.2  | 33.3 | 48.3 | 51.6 | 7.2  | 2.0  | 12.3 | 4.4  | 4.2  | 2.6  | 4.3  | 14.9 |
| J5          | 8.0    |      |      |      | 1.2  |      | 4.1  | 5.2  | 10.6 |      |      | 2.9  |      | 22.2 | 21.7 | 15.8 | 1.6  | 18.2 |      |      | 3.1  | 1.3  | 3.1  | 2.0  |
| J4          | 4.0    |      |      |      | 0.3  |      | 4.6  |      | 11.4 |      |      | 2.4  |      | 1.2  | 1.4  | 8.4  |      |      |      |      |      |      |      |      |
| J3          | 0.5    | 1.4  | 0.7  | 4.9  | 0.9  |      | 3.6  |      | 8.1  |      |      | 3.5  |      |      | 2.1  | 4.7  |      |      | 19.9 | 2.2  | 2.2  | 3.1  | 1.5  | 17.8 |
| J2          |        |      |      |      | 0.3  |      |      | 2.2  |      |      |      | 0.6  |      |      |      |      |      |      | 1.3  | 0.6  | 0.3  | 0.3  |      |      |
| J1          |        |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      | 2.5  |      |      |      |      |      |
| S25         | 4.0    |      |      |      | 4.2  |      | 1.3  | 2.31 | 5.9  |      |      | 1.8  | 2.3  | 9.9  | 3.5  | 7.4  |      | 2.0  | 0.9  | 13.9 | 1.1  | 0.5  | 2.1  | 12.9 |
| S24         | 3.5    |      |      | 1.2  | 3.0  | 6.3  | 1.8  | 1.2  | 16.2 |      |      | 2.4  |      | 0.6  |      | 1.1  |      | 11.0 | 0.9  | 3.3  | 1.7  | 2.3  | 1.5  | 14.9 |
| S23         | 0.5    |      |      | 3.7  | 1.2  |      | 1.8  |      | 13.1 |      |      |      |      |      |      |      |      | 1.0  | 2.1  | 1.7  | 0.6  | 3.6  | 1.5  | 15.8 |
| S22         |        |      |      |      | 0.6  |      |      |      |      |      |      |      |      |      |      | 0.5  |      |      |      | 1.1  |      |      |      | 1.0  |
| S21         |        |      |      |      |      |      |      |      |      |      |      |      |      |      |      | 0.5  |      |      | 0.4  |      |      |      |      |      |
| S20         | 0.5    |      |      |      |      |      | 0.3  |      |      |      |      |      |      |      | 0.7  |      |      | 0.5  |      |      |      |      |      |      |
| S19         |        |      |      |      | 0.3  |      |      | 0.3  |      |      |      |      |      |      |      |      |      |      |      |      |      | 0.3  | 0.3  |      |
| S18         |        |      |      |      |      |      |      | 2.2  |      |      |      |      |      |      |      |      |      |      |      |      |      | 0.3  |      | 3.0  |
| S17         |        |      |      |      |      |      |      | 0.6  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| S15         |        |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| S14         |        |      |      |      |      |      |      |      |      | 1.0  |      |      |      |      |      |      |      |      |      |      |      |      |      | 1.0  |
| S13         |        |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      | 0.3  |      |      |
| S12         |        |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      | 0.3  | 0.3  |      |      |
| S10         |        |      |      |      |      |      | 0.3  |      |      | 1.0  |      |      |      |      |      |      |      |      |      |      |      | 0.3  |      |      |
| S9          |        |      |      |      |      |      |      | 0.3  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| S8          |        |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| S5          |        |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      | 3.0  |      |      |      |      |      |      |
| S4          |        |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      | 0.3  |      |      |      |
| L5          |        |      |      |      | 0.6  |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      | 0.6  |      |      |      |
| No. zircons | 199    | 73   | 155  | 82   | 330  | 16   | 389  | 173  | 359  | 105  | 152  | 170  | 171  | 171  | 143  | 190  | 125  | 200  | 236  | 180  | 359  | 387  | 328  | 101  |

| Zircon population indices |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |
|---------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| IA                        | 669             | 696             | 698             | 672             | 676             | 688             | 665             | 690             | 546             | 697             | 700             | 664             | 696             | 664             | 665             | 638             | 698             | 678             | 563             | 657             | 674             | 666             | 674             | 522             |
| IT                        | 671             | 622             | 597             | 629             | 588             | 413             | 718             | 682             | 730             | 283             | 330             | 686             | 406             | 699             | 765             | 779             | 324             | 470             | 781             | 722             | 575             | 574             | 670             | 735             |
| $\alpha$                  | 57 <sup>a</sup> | 64 <sup>a</sup> | 68 <sup>a</sup> | 57 <sup>a</sup> | 50 <sup>a</sup> | 70 <sup>a</sup> | 61 <sup>a</sup> | 45 <sup>a</sup> | 42 <sup>a</sup> | 75 <sup>a</sup> | 90 <sup>a</sup> | 45 <sup>a</sup> | 80 <sup>a</sup> | 69 <sup>a</sup> | 63 <sup>a</sup> | 27 <sup>a</sup> | 83 <sup>a</sup> | 61 <sup>a</sup> | 38 <sup>a</sup> | 30 <sup>a</sup> | 57 <sup>a</sup> | 45 <sup>a</sup> | 58 <sup>a</sup> | 36 <sup>a</sup> |
| T                         | 835             | 810             | 800             | 815             | 790             | 705             | 860             | 840             | 865             | 645             | 665             | 845             | 700             | 850             | 880             | 890             | 860             | 735             | 890             | 860             | 785             | 835             | 835             | 865             |



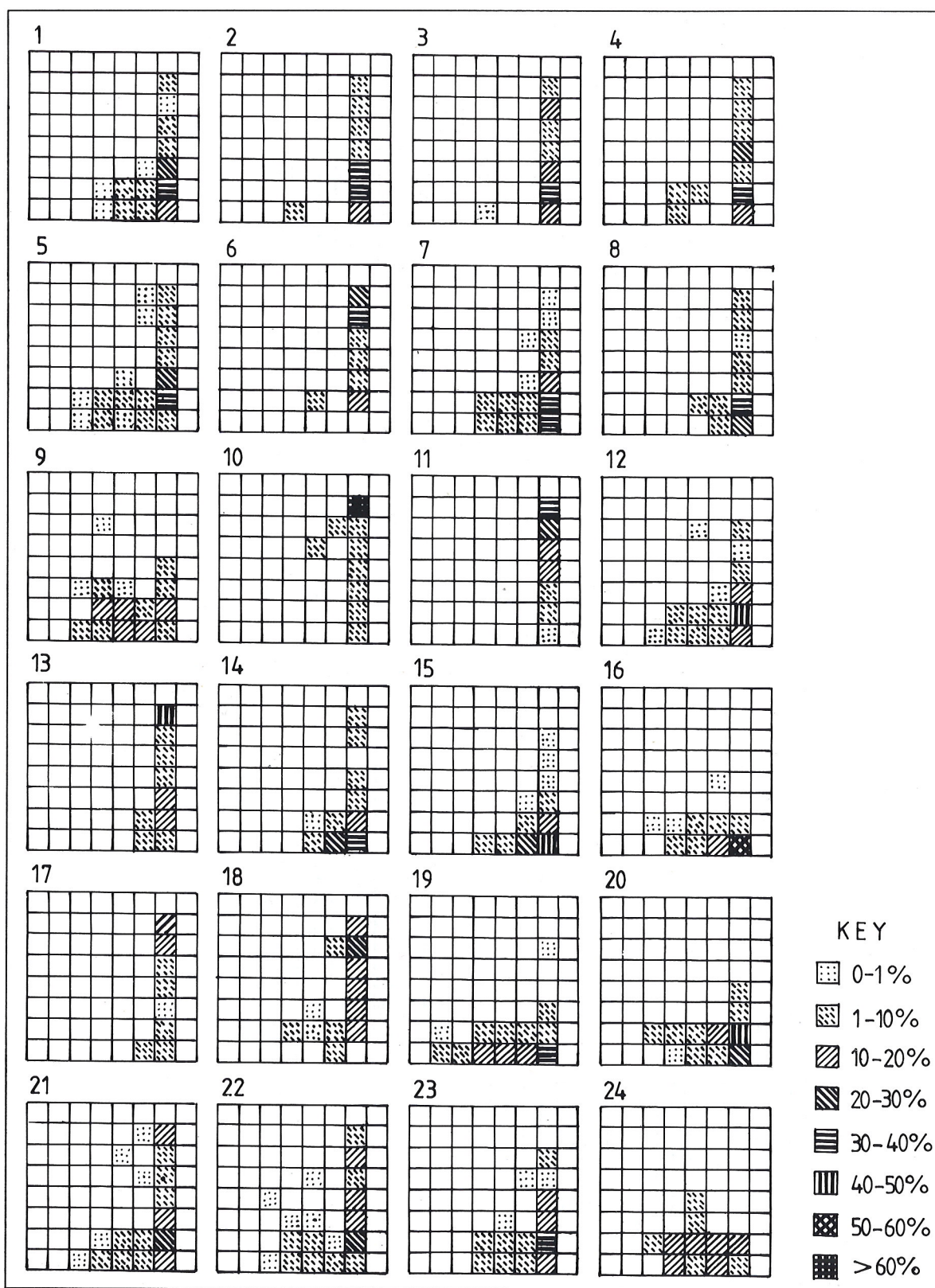


Figure 5 - Typologic distribution of zircon populations from granitoids and tuff

tion may be up to 9.

2. Most of the samples do not have similar heavy mineral assemblages except for a few individuals mentioned above. The most common heavy min-

erals found are magnetite, ilmenite and zircon. Zircon is the ubiquitous mineral in granitoids, but generally it is less abundant in megacrystic fine-grained granite.

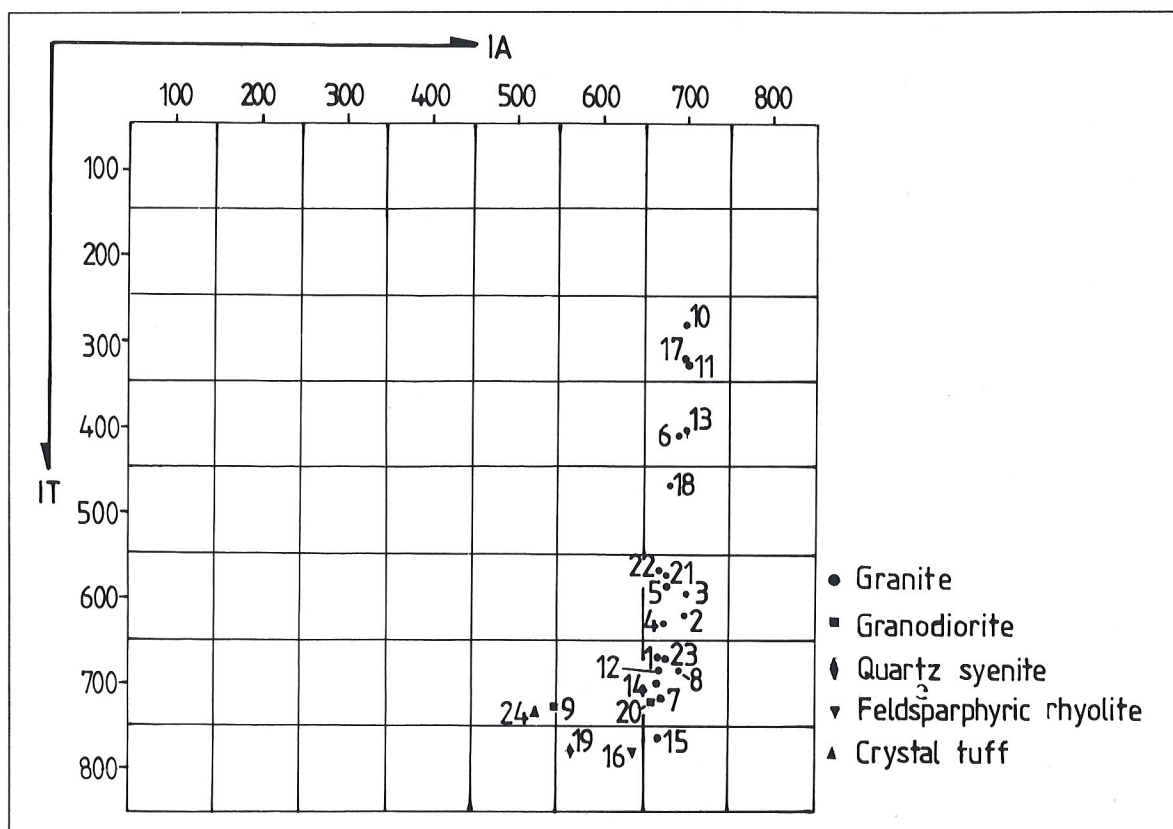


Figure 6 - Distribution of mean points (IA,IT) of zircon populations of granitoid rocks and crystal tuff

| Sample | Zircon               |                          |
|--------|----------------------|--------------------------|
|        | Transparent crystals | Translucent crystals     |
| 21     |                      | 651 — IA — 697           |
|        |                      | 737 — IT — 423           |
|        |                      | 30 — $\alpha$ — 71       |
|        |                      | 870° — T — 710°          |
|        |                      | 175 — Total zircon — 184 |
| 22     |                      | 637 — IA — 693           |
|        |                      | 707 — IT — 448           |
|        |                      | 36 — $\alpha$ — 64       |
|        |                      | 850° — T — 725°          |
|        |                      | 188 — Total zircon — 199 |
| 23     |                      | 659 — IA — 693           |
|        |                      | 728 — IT — 600           |
|        |                      | 34 — $\alpha$ — 50       |
|        |                      | 865° — T — 800°          |
|        |                      | 181 — Total zircon — 147 |

Key referred to Fig. 5

Figure 7 - Typologic distribution of transparent and translucent zircon populations from granitoids



Table 7 - Percentages (by weight) of heavy accessory minerals of the SG &gt; 3.3 fraction

| Sample No. * | Mag   | Ill   | Zr    | Mon   | Xen   | Th   | Sp   | Lim   | Ana  | Gan   | Epi  | Wol   | Cas   | Py | Tou | Mo   | Hem  | T      |
|--------------|-------|-------|-------|-------|-------|------|------|-------|------|-------|------|-------|-------|----|-----|------|------|--------|
| 1            | 93.30 | 0.31  | 0.44  | 5.82  | 0.008 |      | 0.11 | 0.004 |      |       |      | 0.018 |       |    |     |      |      | 4.5430 |
| 2            | 93.24 | 6.16  | 0.17  | 0.43  |       |      | tr   |       |      |       |      |       |       |    |     |      |      | 0.2339 |
| 3            | 11.17 | 46.81 | 3.19  | 31.38 | 5.32  |      | 1.60 |       |      |       |      | 0.53  |       |    |     |      |      | 0.0188 |
| 4            | 56.56 | 24.30 | 0.86  | 17.85 |       | 0.43 |      |       |      |       |      |       |       |    |     |      |      | 0.0465 |
| 5            | 96.65 | 0.70  | 0.38  | 1.94  | 0.07  | 0.25 |      |       |      |       |      |       |       |    |     |      |      | 0.9238 |
| 6            |       |       | 30.60 |       |       |      |      |       |      |       |      | 8.16  | 61.22 |    |     |      |      | 0.0049 |
| 7            | 36.39 | 14.80 | 48.52 | 0.14  | 0.14  |      |      |       |      |       |      |       | tr    |    |     |      |      | 0.0742 |
| 8            | 74.12 | 21.08 | 4.79  | tr    |       |      |      |       |      |       |      |       |       | tr |     |      |      | 0.0313 |
| 9            | 71.85 | 5.39  | 20.96 | 1.20  | 0.60  |      |      |       |      |       |      |       |       |    |     |      |      | 0.0167 |
| 10           | 5.13  | 0.86  | 11.96 |       | 0.86  | 3.42 |      | 10.25 |      |       |      | 25.64 | 41.88 |    |     |      |      | 0.0117 |
| 11           | 17.00 | 81.50 | 1.40  | 0.06  | 0.04  | 0.05 |      |       |      |       |      |       |       |    |     |      |      | 2.1969 |
| 12           | 38.07 | 56.55 | 1.49  | 3.71  | 0.11  | 0.05 |      |       |      |       |      |       |       |    |     |      |      | 0.4362 |
| 13           | 53.10 | 1.80  | 5.30  | 4.12  | 0.09  | 0.23 |      |       |      |       |      | 34.66 | 0.64  |    |     |      |      | 0.3445 |
| 14           | 0.55  | 46.10 | 53.00 |       |       | 0.11 | 0.17 | 0.15  |      | tr    | 0.02 |       |       |    |     | tr   |      | 3.0871 |
| 15           | 45.70 | 11.30 | 43.50 |       |       |      |      |       |      |       | 0.04 | 0.05  |       |    | tr  | tr   |      | 0.4694 |
| 16           | 10.80 | 73.10 | 16.00 |       |       |      |      |       | tr   | 12.70 |      |       |       |    |     |      |      | 1.9630 |
| 17           | 80.70 | 4.60  | 1.90  |       |       | tr   |      |       |      |       |      |       |       |    |     |      |      | 0.6219 |
| 18           | 22.40 | 2.30  | 75.30 |       |       | tr   |      |       |      |       |      | tr    |       |    |     |      |      | 0.0787 |
| 19           | 47.40 | 4.20  | 47.80 |       | 0.02  |      |      | 0.37  | 0.02 |       | 0.18 |       |       |    |     |      | 0.04 | 0.5366 |
| 20           | 0.86  | 6.93  | 90.3  |       | 1.50  | 0.12 |      | 0.26  |      |       |      |       |       |    |     |      |      | 0.4128 |
| 21           | 8.20  | 1.68  | 77.20 |       |       | 0.63 |      | 8.50  | 3.78 |       |      |       |       |    |     |      |      | 0.0952 |
| 22           | 2.47  |       | 86.90 | 8.78  |       |      |      | 1.16  | 0.65 |       |      |       |       | tr | tr  |      |      | 1.9630 |
| 23           | 18.33 | 6.57  | 59.17 | 10.73 | 1.73  |      |      | 2.07  | 0.34 |       |      | 0.69  |       |    |     | 0.34 |      | 0.0289 |
| 24           | 2.43  | 0.49  | 96.20 |       |       |      |      | 0.85  |      |       |      |       |       |    |     |      |      | 0.0822 |

\* Sample descriptions see Table 1

Mag - Magnetite Ill - ilmenite Zr - Zircon Mon - Monazite Xen - Xenotime Sp - Sphene Cas - Cassiterite Wol - Wolframite  
 Th - Thorite Lim - Limonite Py - Pyrite Ana - Anatase Gan - Garnet (almandine) Epi - Epidote Tou - Tourmaline  
 Mo - Molybdenite Hem - Hematite tr - trace T - Total weight in grams

3. Zircon crystals of the plutonic granitic rocks are mainly of types G, P and D. Based on typologic distribution of zircon populations and distribution of mean points (IA, IT), the granitic rocks fall into Pupin's category of alkaline series granites of mainly mantle origin, but no alkaline minerals can be ob-

served. Most granitic rocks (coarse- to medium-grained and partly megacrystic fine-grained) are of deeper source series, but certain granitic rocks (megacrystic fine-grained and partly medium-grained) may be formed near roof of relatively shallow source series. Granodiorite may have complicated chemical



characteristics varying from calc-alkaline to subalkaline series. Quartz syenite, feldsparphyric rhyolite and crystal tuff are tentatively considered to be of calc-alkaline (or subalkaline) series granites of crustal + mantle origin. Most of the granitoid rocks had subjected to pneumatolytic processes in different degrees.

4. The zircon crystallization cycle can be of long duration covering the entire magmatic stage with transparent zircons crystallized earlier than the translucent ones.

5. In this paper, size, shape and colour of zircon, as well as heavy mineral assemblages are not indicative in distinguishing different igneous rocks of the same rock type of different intrusive phases. Typologic distribution of zircon populations is used as a guide to distinguish chemical characteristics of crystallization media.

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## Appendix 1

### The alkalinity ratio

$$\frac{(Al_2O_3 + CaO + \text{total alkalis})}{(Al_2O_3 + CaO - \text{total alkalis})}$$

(all in weight %)

When  $SiO_2$  exceeds 50% and  $K_2O : Na_2O > 1 < 2.5$ , than  $2(Na_2O)$  is used in place of the total alkalis in the expression.

## Cracks In Colluvium, Hong Kong

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### Abstract

The microcrack picture in weathered rhyolitic colluvium in mid-levels Hong Kong indicates the elastic behaviour of clay (halloysite, kaolin) and some possible analogs with macrocracks. New features are the welling up of iron solutions in microcracks, painting and then coating and cementing the clay. Other solutes may occur but are invisible; for example silica.

### 摘要

在香港中環的風化流紋岩的崩塌堆積物中微裂紋景象表示埃洛石、高嶺土等黏土礦物的彈性作用和一些可能是類似微裂紋。它的新特徵是微裂紋流出鐵質溶液、塗膜主粘合黏土，其他如氧化硅溶液可能出現但卻是無形的。

### Introduction

Cracking is of interest to the metallurgist, the engineer, the soil mechanics expert and the geologist (Bisdorn 1967; Whalley and others 1982). In soils macroscopic clay cracks are related to density and compaction which may go hand in hand (Ingles 1969).

In Hong Kong colluvium from landslides has a size distribution following Rosin's law of crushing. Macro fragmentation shapes are fractal (Korvin, 1992). The silicate minerals weather to halloysite and kaolin which compact to "mud" rocks with a content of fine quartz. According to measurements of water content and/or temperature the mud may be brittle (hot dry) or plastic (warm wet).

### Visual Examples

Scanning electron microscope pictures will be used here to introduce the series. A plastic tear is shown in Plate 1, looking like wet cardboard. In contrast an elastic brittle crack is shown in Plate 2. On inspection, Plate 3 reveals a lopsided impact fracture system similar to that in some diamictites (Harker, 1993). Void cracks can occur and are shown in Plate 4. They are due to shrinkage or lack of deposition and are probably incipient full cracks (Termonia and Meakin, 1986). Extrusion of halloysite from a feldspar cleavage crack in Plate 5 demonstrates expansion in weathering. Rounding (Plate 6) is advanced stress corrosion of incipient or sealed microcracks when there is a reentrant giving a split-level shape. Pressures concentrate at reentrants and desorption is fastest there (cf Sprunt and Nur, 1977; Barnett and

Kerrich, 1980). In Plate 7 smearing may be primary or secondary but is associated with very loose grains or cracks. It is primary in plastics where it leads to coatings of cement (Kinloch and Young, 1983). Finally a macroscopic picture of Hong Kong mid-levels colluvium (Plate 8) is composed of boulders and cobbles in a matrix of gravel, sand and mud. Whether microcracks, like crazes in plastics, join up giving larger cracks is partly explored in Table 1.

### Cement

What makes clay brittle enough to crack - compaction, water suction on drying, and/or cement? Cements can be iron oxide, sesquioxide, silica or other. Iron oxide and silica are gradually released on weathering (Figure 1) and ferrous iron oxidises to ferric iron (Figure 2). The smearing of iron oxide paint precipitates (Hsu, 1972) to cement at the crack rim (Plate 7) and is common in micromorphology too (Ruxton, 1987). Sesquioxides, including manganese, are little known in Hong Kong. Rockforming andalusite in the Mesozoic may be from bauxite at Victoria Peak (only water subtracted) and lilac staining in colluvium denotes manganese. Manganese lines cracks in bedrock too. Cements may soften with age. Aluminium goethite softens in plastic bags in 14 years, in water in 5 years and with oxalate solution in 3 years.

Porosity of the colluvium is 42 to 30% with dry density of 1.2 to 1.7 kNm<sup>-3</sup> (Anon, 1982). The strength is determined by the matrix, by the amount of argillisation of the boulders, and by the cement.



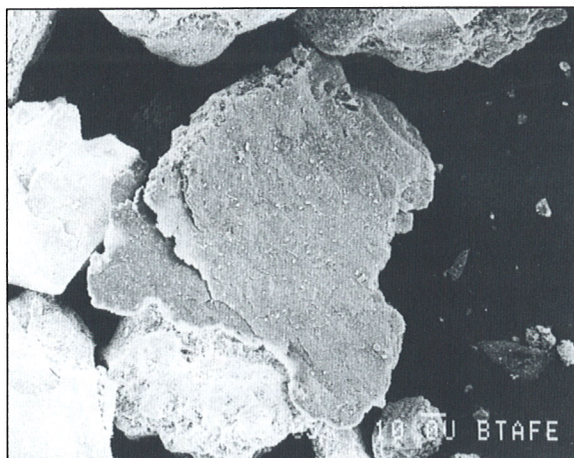


Plate 1 - A plastic tear in laminated clay grain which appears moist. Thickness 10 $\mu$ m.



Plate 2 - Elastic brittle crack 0.5-1.0 $\mu$ m wide. Domain change toward crack from loose, compacted, to cemented.



Plate 3 - Marginal impact fracture system probably from pestle. Longest Crack is 15.6 $\mu$ m.

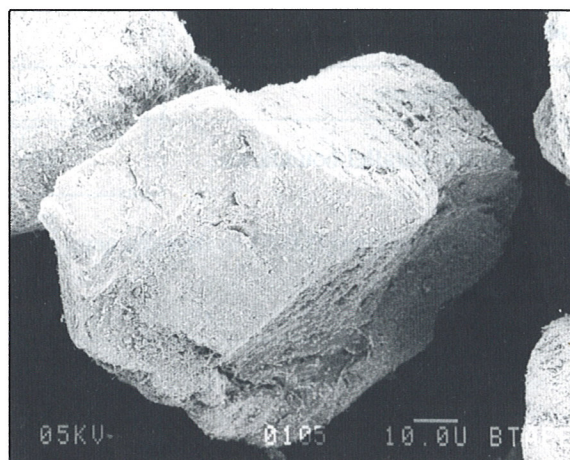


Plate 4 - Internal shrinkage voids in Rhomboidal Laminated clay grain. It appears flat fragment has just spalled off. Short axis of Rhomb 6.3 $\mu$ m.



Plate 5 - Felspar cleavages exuding halloysite crystals 4 $\mu$ m long. Crack or grain boundary on left.

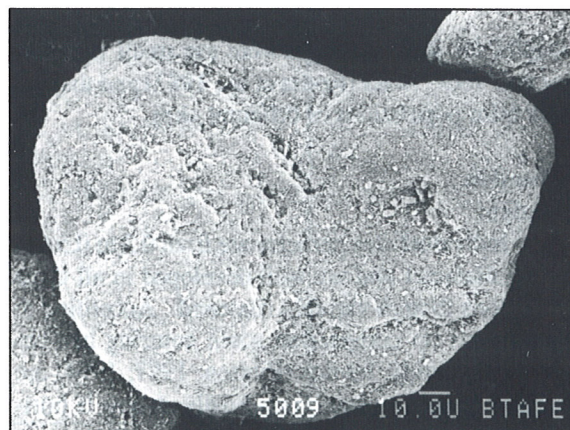


Plate 6 - Stress corrosion etching of rounded large grain 16 $\mu$ m long - higher sw corner separated by incipient fractures from lower level.





Plate 7 - Iron oxide paint associated with cracks probably due to water overflowing. Widest dark band 2 $\mu$ m. Family of cracks obscured by mineral dust.



Plate 8 - Rhyolitic boulder colluvium ranging from clay to boulders. Scale is 30 cm.

Table 2 - Scalar Cracking<sup>1</sup>

| Microscopic                | Macroscopic         | Remarks          |
|----------------------------|---------------------|------------------|
| Sharp, parallel boundaries | Dry cracks          | Brittle fracture |
| Tear                       | Sloughing off       | Moist plastic    |
| Percussion                 | Glacial Diamictites | Probably Pestle  |
| Internal                   | Crevasses           | "Shrinkage"      |
| Cleavage                   | Joint               | Lining           |
| Flat (no movement)         | Planar (Movement)   | Macroshears      |
| Grain breakage             | Landslide breakage  | Fragmentation    |

<sup>1</sup> Fractal aspects given by Korvin (1992)

Samples for shear strength were too small to represent the "rock" mass (Rodin et al., 1982) and they all came from populations of different sites.

## Discussion

### (a) Fabric

Individual clay particles are from 0.2 to 0.5  $\mu$ m in long diameter and are well developed in all three dimensions though variably flattened. According to observations on compaction some suturing has occurred. Granoidic fabrics (Ruxton, 1987; 1994) are confined to soil profiles (principally A and B horizons).

The coarse silt and sand-size grains are made up of three kinds of base -

- (a) clay grain pseudomorphs after silicates,
- (b) authigenic clay grains (Aylmore 1960),
- (c) polymorphs, kaolin, halloysite (Tsuzuki and

Kawabi, 1983).

Kaolin is not obvious in photographs but was identified by x-ray diffraction.

### (b) Slopewash

On Victoria peak the colluvial complex is a sheet on 38° slopes leading down to  $\phi/2$  slopes with abundant seepages. Fluctuating water tables cause paint to become cement and become brittle allowing microcracks. Perhaps both surface slopewash and sub-surface fluctuations may cause alternations of iron rich (8%) and iron poor (4%) laminae 3 to 5  $\mu$ m thick.

## Appendix

Various soft and hard methods of mechanical analysis were tried, among them, oven drying at 110°C, pounding with pestle and mortar, and dispersal with sodium hexametaphosphate. Most of the sam-

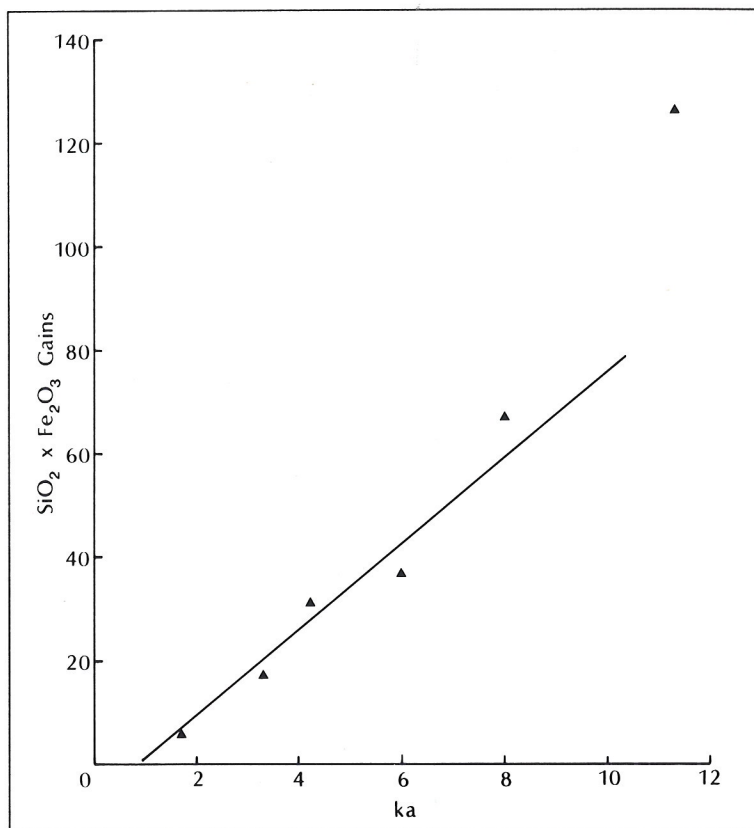


Figure 1 - Si O<sub>2</sub> times ferric against time. There is a sudden jump upwards at 10,000 years as a new sequence of old soil is entered.

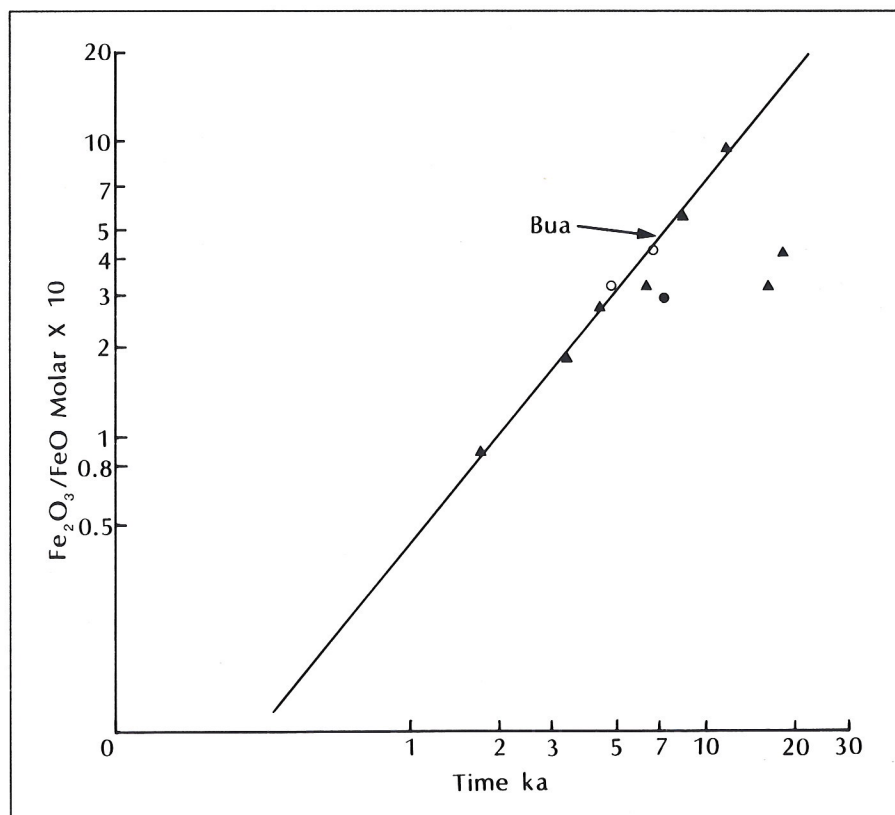


Figure 2 - Ferric over ferrous against time. Right hand triangles corrected as circles. Weathering is needed to produce much ferric.

ples described here were sieved wet with no pretreatment using chlorinated tap water which flocculates the clay. The dispersing agent causes a dusting on the grains of clay particles and possibly some smearing of streaks. Overlong exposure to the dispersion medium, especially if sodium carbonate is added, could explain etching notches and abnormal rounding.

The faces of the grains are often parallel with previous bounding fractures and fragmentation into several geometric forms are seen; parallelipeds, pyramids, rhombs and so on.

Confined subsurface water flow occurs on steep slopes and micropores crossing scanning electron microscope layers show a vortex at the entrance.

In this study samples were collected from borehole cores principally to carry out shear strength tests. Some iron cementation was apparent, at 5% FeO, though usually over 10% FeO is necessary to noticeably affect strength. At mid-levels iron cementation, along with suction, caused the highest angles of friction (36°).

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## Preparation Of Hong Kong Soil Monoliths

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### Abstract

Two soil monoliths have been prepared for use as teaching aids in pedology. The soils, which were collected from two very different soil landscapes in the New Territories, have been preserved by impregnating them with special resins, so preserving their natural soil structures, horizons and colours. These monoliths may be used as visual aids to help illustrate in the classroom some typical characteristics of Hong Kong soils, and to reinforce basic soil science principles.

### 摘要

本研究選用兩種土壤標本輔助土壤學教學。標本選自新界兩種不同地形，並浸滲特殊松香，使其天然之土壤結構、高度及顏色得以保護。這些標本可不斷在課堂上用作形象教學輔助物，闡明香港土壤的特徵並加深對土壤科學基本原則之理解。

### Introduction

A soil monolith is a natural soil profile, collected in the field and transported to the laboratory for preservation and display (Smith and Atkinson, 1975). The principal purpose of collecting soil monoliths is to assist instruction in soil science. A range of soil taxonomic units or soil types can be preserved and used to illustrate soil profile characteristics (e.g. soil structure, colour, special accumulations) and to explain the influence of soil-forming processes on profile development. Monoliths have a far greater visual impact than colour photographs or soil profile sketches and thus they are valuable teaching aids.

Comparison of profiles from a particular locality or landscape allows us to broadly assess the relative influence or importance that the various soil forming factors (climate, vegetation, relief, parent material, time) have had on soil profile development. Ideally, these concepts are best taught and illustrated in the field by examination of a variety of soils from a variety of landscapes. In an environment such as Hong Kong, however, where students have limited opportunities for descriptive field study of Hong Kong soils and their environs, soil monoliths can provide a very practical, tangible, and visual medium of instruction, not only in soil science, but also agricultural science and soil engineering.

This paper documents the first attempt to prepare soil monoliths in the Territory and to establish a reference collection of Hong Kong soils. We necessarily provide a summary of procedures used to pre-

pare two soil monoliths for use as teaching aids in pedology (Plate 1). These procedures are based on both published (van Baren and Bomer, 1979) and unpublished works (Fitzpatrick, c. 1962; Pollock, pers. comm.).

### Methods

#### *Choosing the soil site*

Knowledge of the local soil variation is essential when deciding where to sample representative soil profiles. To identify useful sites we referred to Tang's (1994) soil survey of the Kam Tin region in which the author informally defines six soil classes and maps their distributions. In addition we undertook a preliminary survey of neighbouring hillslopes ourselves. We selected two soil types from two very different soil landscapes in the New Territories. The first, a gley soil, was taken from a lowland site near Shui Tau village in Kam Tin which was formerly used for agriculture and is currently used for buffalo grazing. This soil belongs to Tang's (1994) soil class F. The second, a hill soil developed in weathered predominantly granitic colluvium, was collected from a landslide scarp exposed on a hillside in Lam Tsuen Valley, and is representative of soils belonging to Tang's (1994) soil class E.

The two soils chosen exhibit features which, without examination in the field and thus reference to actual examples, are difficult for students to conceptualise. The man-modified agricultural soil contains both concretions and iron-mottles, and is valu-

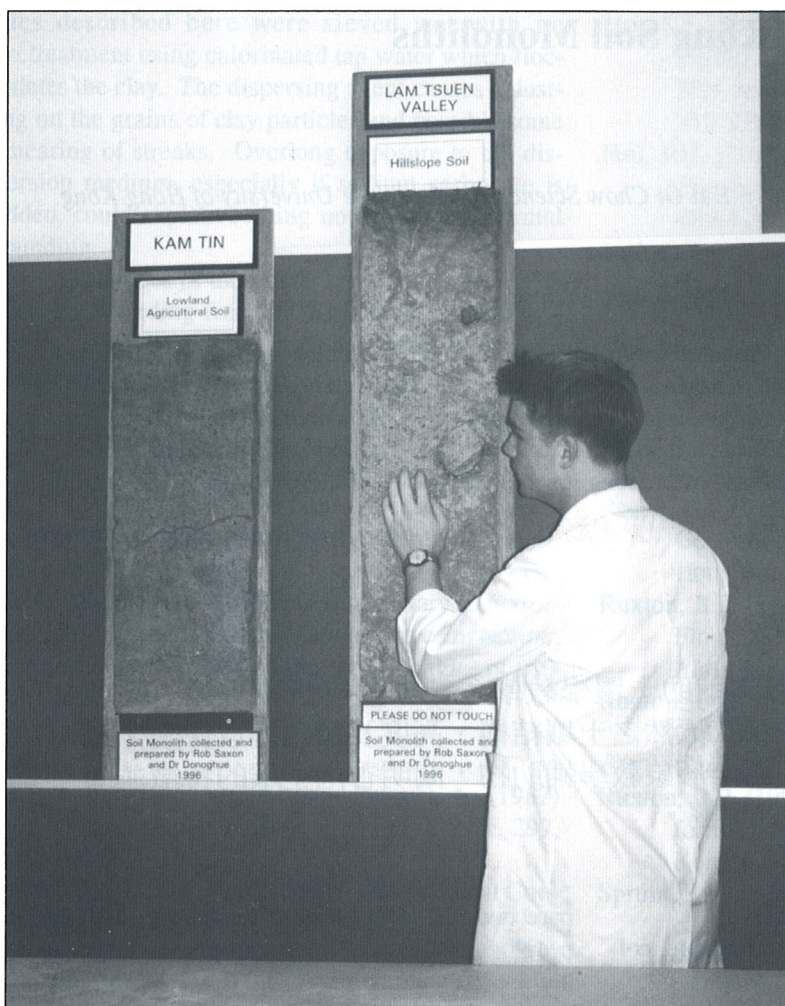


Plate 1 - The soil monoliths on display in the laboratory.

able in explaining the impact that stock trampling has on soil structure and root penetration, as well as soil characteristics which develop under alternating redox conditions caused by seasonal fluctuations in water tables. The hillslope soil is useful in explaining weathering of parent materials, the influence of colluvial additions (in hillslope environments) on profile characteristics, and the influence of organisms in developing strongly structured topsoil horizons.

#### *Collecting the soil profile*

For a detailed account of the field procedures used to collect soil profiles readers are referred to van Baren and Bomer (1979). Additional useful comments are also given by Pollock (pers. comm.) and Fitzpatrick (c. 1962). Here, we provide a summary of the relevant procedures.

Soil profiles are collected in the field using a framed wooden box, made of strong plywood and held together with screws so that the backboard and frame can be detached. These are easily designed and assembled in Departmental workshops. Dimensions are typically about one metre in length, 20 cm width, and 10 cm depth (Pollock, pers. comm.). Monoliths much

larger than this are generally too difficult to collect and transport.

For the hillslope soil we used a box 1 metre in length to enable us to sample interesting subsoil horizons. For the lowland agricultural soil, where the water table was at 80 cm depth below the soil surface, we used a shorter (75 cm) box.

At the field site, the back of the box is removed, leaving the frame intact. The frame of the box is then held against the soil face (i.e. either the face of an existing exposure or the face of an excavated soil pit), and then using a sharp knife, the outline of the frame is traced onto the soil face. This trace should be a little larger than the frame to allow for later trimming. The frame is then withdrawn and the soil surrounding this outline gradually and carefully cut back, to a depth a little greater than that of the frame, to create a protruding soil block.

The frame is then placed over the protruding soil block, ensuring that the profile fits snugly into the frame and will be flush with both the back and frame. The back of the box is then re-attached. Care is needed to ensure that the edges of the soil block do not crumble away or become dislodged during this

procedure. One or two persons are required to hold the box in place while another then slowly levers the block away from the bank, ensuring that the levered block is at least 10 cm deeper than the box itself. This extra depth helps minimise damage to the soil column during levering and will later be cut away. Once in the box any spaces or cracks in the profile may be filled with soil taken from the appropriate horizon. Bandages or strips of cloth are then tightly wrapped around the soil and box to minimise flexing of the soil column and to provide support during transportation back to the vehicle, (Pollock, pers. comm.; van Baren and Bomer, 1979).

The soil profiles are left for a period of time to allow the soil to partially dry so that soil preserving solutions applied to the soil surface can more readily and thoroughly infiltrate the soil (Fitzpatrick, c. 1962). In our case the soils, which were lightly wrapped in cloth and protective plastic, were left to partially air-dry for six months.

The excess protruding soil is carefully cut away (using for example a broad bladed knife or metal paint scraper) so that the profile is flush with the frame of the box. This surface will become the backside of the monolith and will be glued to a display board so it is important that the cut surface is uniformly flat. Any cracks, gaps or hollows present may be carefully packed with soil saved during cutting down. The profile is now ready for impregnation with resin (Pollock, pers. comm.).

#### *Laboratory preservation of the soil profile*

The preservation of soil profiles involves impregnating the entire profile with resin, thus preserving the natural soil structure, soil horizons and soil colour. In this study we largely followed the procedures detailed in van Baren and Bomer (1979), as well as modifications to these which were recommended and communicated to us by Dr. Jim Pollock, a research fellow at Massey University who for many years has collected and prepared monoliths of New Zealand soils. We also made our own modifications to published procedures, as necessary, in order to cope with the marked contrast in textural and structural properties of the two soils collected. This contrast in soil types proved useful in testing the methodology in the Hong Kong context since many different types of soils exist in the Territory. Here we provide a summary of the preservation procedures.

Cellulose acetate resin is used to preserve the soil profile. It is prepared by dissolving cellulose acetate in acetone (Fitzpatrick, c. 1962). Two concentrations are used. Dilute resin is first applied because it is less viscous and more easily infiltrates the soil profile. This is poured evenly over the cut soil surface and allowed to infiltrate. For safety, to reduce inhalation of acetone vapour, we prepared the resin in a fume hood, and also placed the soil profile in the

fume hood when applying the resins. Although the complete profile could not be accommodated in the fume hood because of its size, sufficient ventilation was achieved.

Fitzpatrick (c. 1962) suggests around 300-600 ml of dilute cellulose acetate is sufficient to seal most soil profiles, and that more concentrated resin may be applied to more porous soils. We first applied 600 ml of dilute resin to each profile, but found considerably more resin was required to thoroughly seal the soil. We thus applied a further 600 ml of concentrated resin to the more dense lowland agricultural soil, and 1200 ml of the same to the more porous hillslope soil. Preparation of the resins, and the impregnation of the profiles took around 4-6 hours per profile. It is very difficult to gauge to what depth the resins have infiltrated the profile, and therefore what volume of resin to use. We chose to continue to apply the resin until it temporarily ponded at the soil surface, suggesting near saturation.

#### *Mounting on a display board*

Once the concentrated cellulose acetate resin has dried, a little more concentrated resin is brushed onto the soil (around 300 ml) and a piece of jute (sacking) the size of the soil block, attached. This is left to dry overnight so that the cloth becomes firmly fixed to the soil. A fast drying glue is then spread over the cloth (we used a locally sourced all purpose glue - 2335 Rubstic Tropic) and a wooden display board, a little larger than the box, placed on top and securely bandaged down to ensure contact with the glue. Pollock (pers. comm.) has never found it necessary to use a jute backing, however, since we had not previously prepared monoliths, we thought it was probably worthwhile doing so to provide extra grip. The profile is then turned over so that the full weight of the profile may assist the bonding process (van Baren and Bomer, 1979).

#### *Cutting down and picking*

The soil profile now has to be cut down to leave about 4 cm depth of soil. To do this the framing and backboard must first be removed from the profile. At this point some repair work may be necessary. We found that in places the edges of the profile were fragile, and in the case of the lowland agricultural soil, the very basal horizon comprising marine sands was still crumbly. Further, a large shrinkage crack developed across the profile requiring filling. As suggested by van Baren and Bomer (1979) we applied additional cellulose acetate to secure the loose soil, and trimmed the profile back to remove weak edges.

The natural structure of the profile is then revealed by carefully picking down the soil, to a final depth of around 3 cm (Fitzpatrick, c. 1962). This is the most difficult task, and for this we referred to Pollock's (pers. comm.) very helpful and descriptive



account of the procedure and its problems.

Structural units are revealed by carefully removing soil with a small pick or pocket knife so that it parts along natural cleavage lines (Fitzpatrick, c. 1962). Loose soil can be gently brushed or blown away. Care must be taken not to "pluck out" structural units and in so doing reveal the back board, or to leave implement marks which create unnatural surfaces (Pollock, pers. comm.). In the case of the lowland agricultural soil, which has an entirely massive structure, we were unable to reveal structure. In the hillslope soil we had some difficulty revealing the blocky subsoil structure, but found it relatively easy to reveal the strong nutt structure of the topsoil horizons and to leave roots intact. Several stones were loosened and had to be secured at their margins with further cellulose acetate resin.

#### *Final lacquering and display*

Polyvinyl acetate solution is applied (poured or gently brushed) to the entire soil surface to restore the natural soil colours and to provide surface protection. This is prepared by dissolving vinylite resin in a 2:1 mixture of acetone and methyl isobutyl ketone. We applied one litre of vinylite resin per profile, as suggested by Fitzpatrick (c. 1962).

Finally, additional supports may be added to the profile, such as steel brackets or aluminium framing before raising the profile. The monoliths are reasonably heavy and so are quite stable if simply placed on a bench or shelf for display, with a slight backward slant. van Baren and Bomer (1979) recommend viewing the profiles under artificial light.

#### **Summary**

The two soil monoliths are now displayed in the Department of Geography and Geology, The University of Hong Kong. Their preparation and subsequent display has attracted much interest from staff and students, so reinforcing our belief that they are a very useful and practical tool of instruction in soil science.

The authors welcome enquiries from colleagues in Hong Kong who might wish to extend this initial work and help create a useful and impressive collection of Hong Kong soils.

It is also worth considering extending this work to include local marine and terrestrial sediment cores. The methodology could be suitably adapted to allow preservation of core cross-sections. These would be very useful in teaching Quaternary geology, and would make excellent geological exhibits.

#### **Acknowledgements**

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his invaluable advice and time taken to prepare written notes on procedures, Mr. I.S. Bell and Dr. M.R. Peart for their tremendous help with the field collection and transport of the soil profiles, and Dr. G. Lin for kindly translating the abstract.

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#### **Appendix: Preparation of resins and chemical suppliers:**

Fitzpatrick (c. 1962) gives volumes in gallons. For convenience we have expressed volumes in millilitres. Solutions are viscous and are best prepared using a magnetic stirrer to avoid clumping and to speed dissolution. Dissolution takes about 1-2 hours per 600 ml solution.

##### *1. Dilute cellulose acetate resin:*

30.8 g of cellulose acetate dissolved in 1000 ml acetone ( $\text{CH}_3\text{COCH}_3$ ).

##### *2. Concentrated cellulose acetate resin:*

99.0 g of cellulose acetate per 1000 ml acetone

##### *3. Vinylite resin:*

52.8 g of polyvinyl acetate dissolved in 1000 ml (total volume) of a 2:1 mixture of acetone and methyl isobutyl ketone (4-methyl-pentan-2-one:  $(\text{CH}_3)_2\text{CHCH}_2\text{COCH}_3$ ). Note - if the acetate is not kept in an airtight jar then it forms a hard clump and is extremely difficult to extract and dissolve.

##### **Chemical Supplier and Costs:**

Union Laboratory Supplies Ltd., Sha Tin, Hong Kong:

1. methyl isobutyl ketone (4-methyl-pentan-2-one:  $(\text{CH}_3)_2\text{CHCH}_2\text{COCH}_3$ ). 1995 quoted price per 2.5 litres HK \$227.16.

2. Cellulose acetate (GPR grade). 1995 quoted price \$HK 169.80 per 500 gm

3. Polyvinyl acetate (LR grade). 1995 quoted price per 500 gm bottle HK \$62.50

## Morphological And Chemical Characteristics Of Upland Volcanic Soils Along A Vegetation Gradient Affected By Hillfire In Hong Kong

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### Abstract

Five representative soil profiles were studied along a vegetation gradient that had experienced fire disturbance at different times. Clear horizonation of the soils was observed. The O and A horizons decreased with successional development. The results of soil chemical analyses varied. Soil pH ranged from 4.25 to 5.11. Soil acidity decreased with depth reflecting the higher content of exchangeable cations, particularly Ca in the C horizons. As succession proceeds, acidity increases. Exchangeable acidity is dominated by Al, and exchangeable K tended to accumulate closer to the top horizons as a result of previous ash deposits. The field observations and the results of the analyses have elucidated the effect of fire and vegetation on volcanic soil profiles.

### 摘要

本文主要研究林火對香港火山岩發育形成的土壤的影響。從大帽山植被演替梯度的三個主要植被分類（草坡地、灌叢、樹林）中，本研究選取了五個曾在不同時期發生過林火的土壤剖面為樣本，發現此五個剖面分層明顯。林火發生後，隨著植被正向演替，土壤 O 及 A 層厚度均呈遞減趨勢。土壤的化學性質也不一致，其中 pH 值測得在 4.15 至 5.11 之間。土壤酸度隨深度減少的規律指示了土壤 C 層中代換性陽離子（尤其是 Ca）的增加。植被的正向演替亦增加了土壤的酸性，其中以代換性 Al 為主。由於過火後灰分留在土表，引致代換性 K 在表土富集。

### Introduction

The modifications to the vegetative cover, soil properties and the production and stability of local ecosystems as a result of the perpetual occurrence of fire in Hong Kong country parks has prompted recent concern. Some recent studies have dealt with vegetation regeneration (Chau 1994) and the immediate effects of fire on soil properties (Yau 1996), but the extent to which fire and vegetation development influences the soil profiles in the humid tropical regions of Hong Kong and South China have not been studied. Elsewhere it has been reported that soils over which fire has passed are usually profoundly degraded (Giovannini *et al.* 1987) as a result of nutrient loss and accelerated erosion and that some of the vegetation may never recover (Thrower 1984).

As one of the major agents of ecosystem disturbance, fire results in the alteration of hydrologic regimes of a site which subsequently affects the movement of soil nutrients and the potential of the soil to

accommodate vegetation. Since a good percentage of this movement is down the profile, a representative study of how these properties vary and how these properties vary with time after fire is necessary. Although soils in general have a number of features in common, individually they tend to differ markedly (Olsson and Melkerud 1989). On top of this fire may alter the soil processes and pathways of nutrient transfer within the soil-plant subsystems. In general, three levels of land disturbance can be identified according to the severity of perturbation. They are in ascending order of severity, vegetation disturbance, soil disturbance and soil destruction (Aber 1990). Although vegetation and soil disturbances are lesser in severity, they occur as a result of fire events.

The soils found in the hilly areas of South China, including Hong Kong, are subject to the influence of high temperature and abundant rainfall (Zhao & Hua, 1986). Although this region is endowed with good hydrothermal conditions that are favourable for

the rapid cycling of nutrients within the soil - plant subsystem, fire frequently interrupts this cycle in the six cool dry winter months (HKG 1996). In a normal fire season in Hong Kong (September to April), there could be as many as 300 fire outbreaks per year (HKG 1996). Therefore hill fires in Hong Kong must be studied as integrated phenomena associated with country park ecosystems and their management.

Indeed the characterization of soils, in order to identify the important similarities and dissimilarities among them, is a lengthy process. However, for certain practical applications, soil productivity and behaviour can be predicted through approximate evaluations of some properties (Hausenbuiller 1978), fire events notwithstanding. The soil gradient associated with the vegetation chronosequence provides an excellent opportunity to study soil property changes, and to highlight such changes as a response to the impact of fire when other factors are held constant. Although most field properties are descriptive, systematic changes in all or part of these descriptions can be found (Harden 1982). The major objectives of this study are therefore threefold:

- (1) To examine the morphology of these soils and to identify specific soil features, if any, at each study site,
- (2) To determine any fire effects that can be depicted from profile morphology and some basic soil chemical properties, and
- (3) To distinguish any variability, either morphologically or in soil chemical properties, along the vegetation gradient.

#### Study Site Characteristics

The study area covers the Tai Mo Shan Country Park area. The Tai Mo Shan Country Park comprises an area of 1 440 hectares of land. It is bordered by the Tai Lam and the Shing Mun Country parks and is located on the North Western part of the New Territories. Since the country parks are divided into compartments to facilitate management, specific study sites were located in individual compartments.

The geology of Tai Mo Shan is a sequence of faulted, folded, mildly metamorphosed volcanic rocks that are extensively intruded by younger igneous rocks and partially overlain by a variety of superficial deposits (GASP 1987). Tai Mo Shan Country Park is made up entirely of volcanic rocks, mostly coarse tuff with finer tuffs and lava deposits in the marginal areas (Grant 1960, Thrower 1984, GASP 1987). The volcanic rocks comprise lavas and explosively erupted pyroclastic deposits of tuff, agglomerate and volcanic breccia, and are generally rhyolitic in composition (Peng 1986).

Tai Mo Shan dominates the landscape in the New Territories in Hong Kong rising to a peak of 957 m asl. Gently convex upper slopes on this mountain give way to steep upper sideslopes on both the North and South. Irregular ridges extend to the east and

southwest of the main summit. Several parts of the SW ridge exceed 500 m in elevation but still possesses gently to moderately steep (15 to 30°) sideslopes with extensive midslope benches. Several major spurs trend approximately N to S under the influence of the drainage pattern (GASP 1987).

Tai Mo Shan, being the highest peak in Hong Kong, sometimes records the highest amount of rainfall. Additional precipitation is added in the form of fog and mist that is characteristic of the mountain range. In addition, this is a high rainfall area due to orographic uplift. These effects further give rise to relatively lower daily temperature than that reported by the Royal Observatory. A difference of between 1 and 3 degrees is not uncommon.

Today, the summit of Tai Mo Shan Country Park supports only a thin vegetation of grassland intermingled with annual and perennial shrubs on some slopes. The shallow valleys also have a few shrubs and support a mixture of tree species most of which were planted by the Agriculture and Fisheries Department. The contemporary vegetation structure is constantly being disturbed by anthropogenic factors, of which fire is most prominent. The annual dry season which starts about the end of September provides many days on which conditions are almost ideal for fires. In the event of fire, grasses, shrubs and smaller trees are killed and many of these plants will never recover (Daley 1975). The vegetation cover basically consists of a mixture of grass species mostly *Miscanthus floridulus*, *Arundinella nepalensis*, *Ischaemum aristatum* and *Scleria herbecarpa*. Intermingled with these grasses are species such as *Melastoma dodecandrum*, *Rhodomyrtus tomentosa*, *Dianella ensifolia* and *Rubus reflexus*. In addition to some of these shrubs, the shallow valleys support popular species such as *Acacia confusa*, *Tristania conferta*, *Castanopsis fissa*, *A. auriculiformis*, *Liquidambar formosana*, *Eucalyptus camaldulensis*, *Melaleuca leucadendron*, *Pinus sp.*, and so on.

#### Methodology

##### (a) Field Methods

In order to examine the inherent variability of soils between sites, five representative soil profiles were studied along a vegetation chronosequence. Soil profiles were dug in February and March 1995, representing the dry season in Hong Kong.

At each of the study areas, a representative location was selected. The above-ground vegetation was carefully cleared before profile pits, each measuring 1 m x 1 m, were carefully dug to various depths, depending on the ease of excavation (Plate 1).

After the soil pit was dug, a description of the soil profile was carried out in accordance with procedures outlined in the FAO classification system (Moormann 1981). Detailed morphological structures were recorded in the field. The boundaries of soil





Plate 1 - Soil profile pit at site F6.

horizons were carefully identified while soil colour was determined by use of the Munsell Soil Colour Chart. Drainage direction and pattern were also observed and recorded. The soil texture and structure were morphologically examined.

Soil samples were taken from each identified horizon, after careful removal of the surface dirt. The samples were replicated 3 times and returned to the laboratory for further treatment and analysis.

#### (b) Laboratory Methods

Soil chemical properties down the profile were examined in an attempt to identify specific effects likely to be caused by fire. Furthermore, the results obtained will provide an insight to the genesis and development of these soils, where fire has been absent for 0 to 17 years.

Upon returning to the laboratory, about 50 gm of fresh soil was immediately passed through 2 mm sieve and kept in the refrigerator at 4°C for the analysis of mineral N and available P. The remaining bulk samples were air-dried, passed through 2 mm and 0.25

mm sieves, respectively. The 2 mm sieved soil samples were used for the determination of soil pH, exchangeable bases (K, Na, Ca and Mg), while the 0.25 mm sieved soils were used for the determination of exchangeable Al and H (Anderson & Ingram 1989), total N and P (Allen *et al.* 1989) and organic C. Soil organic matter content was estimated by multiplying the organic carbon content by a factor of 1.724 (Chaney and Swift 1984). The contents of  $\text{NH}_4$  and  $\text{NO}_3$  was also determined by methods recommended by Anderson and Ingram (1989).

#### Soil Profile Characterization And Description

Detailed description of the soil profiles is presented below. This will be followed by a summary of the major observations from the profile morphology, with particular reference to the impact of fire.

#### Summary Of Morphological Observations

Following the field observations and the profile description, a number of morphological observations were made which are outlined below:

**F<sub>0</sub> Profile (Burnt in March 1994)**

|                       |                                                                                                                                |
|-----------------------|--------------------------------------------------------------------------------------------------------------------------------|
| Physiography          | Upland                                                                                                                         |
| Slope characteristics | 33% convex                                                                                                                     |
| Elevation             | 720 m ASL                                                                                                                      |
| Drainage              | Moderately well drained                                                                                                        |
| Land Use              | Short grassland                                                                                                                |
| Vegetation            | Burnt vegetation include <i>Gramineae</i> spp., <i>Dicranopteris linearis</i> and charred remains of <i>Pinus massoniana</i> . |
| Parent Material       | Volcanic                                                                                                                       |

| HORIZON | DEPTH (cm) | DESCRIPTION                                                                                                                                                                                                                                                                               |
|---------|------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| O       | 0-6        | This is a layer of incompletely decomposed debris. It can be divided into O <sub>1</sub> and O <sub>2</sub> , with abundant fine to very fine roots. Soil is sandy loam and structureless. Soil colour is equivalent to 10YR 3/1, very dark gray. Slightly smooth boundary is noticeable. |
| A       | 6-27       | Layer of humus formation, loamy soil with subangular structure. Very fine roots and stones are present. Colour is 2.5Y 3/3, dark olive brown. Smooth boundary is noticeable.                                                                                                              |
| B       | 27-38      | Layer of illuviation. Loamy soil with subangular structure. Many stones were observed. Colour is 7.5YR 4/6, strong brown. Clear wavy boundary exists.                                                                                                                                     |
| BC      | 38-51      | This is a transitional layer between B and the parent material. Soil is sandy loam and structure is granular. Stones are also noticeable. Colour is 7.5YR 4/4, dark brown. Clear wavy boundary exists.                                                                                    |
| C       | 51-82      | Layer of weathered parent material. Clayey with subangular structure and stones are present. Soil is sticky. Colour is 5YR 4/4, reddish brown.                                                                                                                                            |

**F<sub>1</sub> Profile (Burnt in 1992)**

|                       |                                                                                                                                               |
|-----------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|
| Physiography          | Upland                                                                                                                                        |
| Slope characteristics | 23% convex                                                                                                                                    |
| Elevation             | 550 m ASL                                                                                                                                     |
| Drainage              | Moderately well drained                                                                                                                       |
| Land Use              | Moderately tall grassland of about 1m height                                                                                                  |
| Vegetation            | Grassland vegetation including <i>Ischaemum aristatum</i> , <i>Arundinella nepalensis</i> and scattered shrub species of <i>Inula cappa</i> . |
| Parent Material       | Volcanic                                                                                                                                      |

| HORIZON | DEPTH (cm) | DESCRIPTION                                                                                                                                                                                                                                                                           |
|---------|------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| O       | -5         | Layer of incompletely decomposed material. It can be divided into O <sub>1</sub> and O <sub>2</sub> . Texture is loamy and soil is structureless. Many fine roots are present and ash particles are observed. Soil is very dark gray in colour, 10YR 3/1. Clear wavy boundary exists. |
| A       | 5-21       | Layer of humus formation, Clayey loam soil, subangular blocky. Fine roots and worm casts are noticeable. Soil is slightly sticky, colour is 2.5Y 3/2, very dark greyish brown. Smooth boundary is noticeable.                                                                         |
| AB      | 21-30      | Transitional layer between A and B. Roots are visible. Clayey soil with angular structure. Soil colour is 10YR 4/4, dark yellowish brown. Clear wavy boundary exists.                                                                                                                 |
| B       | 30-47      | Clayey loam soil with angular structure. Very fine roots are noticeable. Soil colour is 10YR 4/6, dark yellowish brown. Soil is slightly sticky. Clear wavy boundary exists.                                                                                                          |
| BC      | 47-69      | Transitional layer to the C horizon. Loamy soil with angular structure. Large stones are noticeable. Colour is 7.5YR 4/6, strong brown. Clear smooth boundary is noticeable.                                                                                                          |
| C       | 69-107     | The layer of parent material. Sandy loamy clay soil with subangular structure. Large stones are present. Evidence of mottling. Soil colour is 5YR 4/4, reddish brown.                                                                                                                 |

**F<sub>3</sub> Profile (Burnt in 1990)**

|                       |                                                                                                                                                                                                         |
|-----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Physiography          | Upland                                                                                                                                                                                                  |
| Slope characteristics | 21% convex                                                                                                                                                                                              |
| Elevation             | 720 m ASL                                                                                                                                                                                               |
| Drainage              | Moderately well drained                                                                                                                                                                                 |
| Land Use              | Well established grassland of about 1-1.5 m height                                                                                                                                                      |
| Vegetation            | Predominantly grassland vegetation of <i>Miscanthus floridulus</i> , <i>Ischaemum aristatum</i> ; some isolated shrubs including: <i>Inula cappa</i> , <i>Smilax china</i> , <i>Breynia fruticosa</i> . |
| Parent Material       | Volcanic                                                                                                                                                                                                |

| HORIZON | DEPTH (cm) | DESCRIPTION                                                                                                                                                                                                                        |
|---------|------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| O       | 0-4        | Layer of partly decomposed debris. Many fine to very fine roots are present. It can be divided into O <sub>1</sub> and O <sub>2</sub> layers. Soil colour is dark greyish brown, 10YR 3/2. Slightly smooth boundary is noticeable. |
| A       | 4-9.5      | Layer of humus formation. Texture is sandy loam and the structure is granular. Very fine roots are present. Dark greyish brown in colour, 2.5Y 3/2. Clear wavy boundary exists.                                                    |
| AB      | 9.5-17     | Transition layer between A and B horizons. Loamy soil with fine gravels present. Structure is granular, colour is 10YR 4/4, dark yellowish brown. Clear wavy boundary exists.                                                      |
| B       | 17-31      | Clayey loam soil with big stones present. Subangular blocky structure, Yellowish brown colour, 10YR 5/8. Slightly sticky soil, with a clear wavy boundary.                                                                         |
| BC      | 31-71      | Transitional layer to the parent material. Structure is subangular blocky. Mottling is evident, with dark reddish brown colour, 2.5YR 3/4. Smooth boundary is noticeable.                                                          |
| C       | 71-111     | Layer of the parent material. Clayey soil with angular structure. Soil is sticky. Over 40% of mottles and coarse fragments are present. Colour is yellowish red, 5YR 5/8.                                                          |

**F<sub>6</sub> Profile (Burnt in 1988)**

|                       |                                                                                                                                                                                                                                           |
|-----------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Physiography          | Upland                                                                                                                                                                                                                                    |
| Slope characteristics | 23% convex                                                                                                                                                                                                                                |
| Elevation             | 750 m ASL                                                                                                                                                                                                                                 |
| Drainage              | Moderately well drained                                                                                                                                                                                                                   |
| Land Use              | Well established mixture of grassland (1.5-2 m high) and scrubland.                                                                                                                                                                       |
| Vegetation            | A mixture of grass and shrub species including: <i>Lycopodium cernuum</i> , <i>Miscanthus floridulus</i> , <i>Ischaemum aristatum</i> , <i>Melastoma candidum</i> , <i>Inula cappa</i> , <i>Rubus reflexus</i> , <i>Eurya chinensis</i> . |
| Parent Material       | Volcanic                                                                                                                                                                                                                                  |

| HORIZON | DEPTH (cm) | DESCRIPTION                                                                                                                                                                                                                                                        |
|---------|------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| O       | 0-1.5      | Completely decomposed organic material. Loamy soil, granular structure. Abundant fine roots. Colour is black, 2.5Y 2.5/1. Clear wavy boundary exists.                                                                                                              |
| A       | 1.5-6      | Layer of organic formation. Loamy soil with granular structure. Many fine to very fine roots are present. Very dark gray colour. 2.5Y 3/1. Clear wavy boundary exists.                                                                                             |
| AB      | 6-11       | Transitional layer of humus formation with an olive brown colour, 2.5Y 4/3. Loamy clay soil with granular structure. Earthworm casts are noticeable; stones and very fine roots are also present. Soil is slightly sticky. Slightly smooth boundary is noticeable. |
| B       | 11-23      | Loamy clay soil with subangular structure. Roots and stones are abundant. Mottles are abundant, about 40%. Colour is dark yellowish brown, 10YR 4/4. Soil is slightly sticky. Slightly smooth boundary is noticeable.                                              |
| BC      | 23-61      | Zone of gradual transition from the above layer to the parent material. Subangular blocky structure. Clayey soil with a yellowish red colour, 5YR 4/6. Sticky soil with a clear smooth boundary.                                                                   |
| C       | 61-90      | Layer of parent material. Clayey soil dotted with large stones, angular structure. Colour is 5YR 4/6, yellowish red. Sticky soil.                                                                                                                                  |



# F<sub>17</sub> Profile (Burnt in 1976)

|                       |                                                                                                                                                                                                                                                                                                                                                                                                              |
|-----------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Physiography          | Upland                                                                                                                                                                                                                                                                                                                                                                                                       |
| Slope characteristics | 21% convex                                                                                                                                                                                                                                                                                                                                                                                                   |
| Elevation             | 430 m ASL                                                                                                                                                                                                                                                                                                                                                                                                    |
| Drainage              | Moderately well drained                                                                                                                                                                                                                                                                                                                                                                                      |
| Land Use              | A mixture of vegetation cover, predominantly woodland.                                                                                                                                                                                                                                                                                                                                                       |
| Vegetation            | Predominantly tree species, with grass and shrub undergrowth: <i>Tristania conferta</i> , <i>Smilax ovalifolia</i> , <i>Sarcandra glabra</i> , <i>Machilus chinensis</i> , <i>M. thunbergii</i> , <i>Psychotria serpens</i> , <i>P. rubra</i> , <i>Litsea rotundifolia</i> , <i>Mallotus paniculatus</i> , <i>Lycopodium cernuum</i> , <i>Acacia confusa</i> , <i>Inula cappa</i> , <i>Ardisia crenata</i> . |
| Parent Material       | Volcanic                                                                                                                                                                                                                                                                                                                                                                                                     |

| HORIZON | DEPTH (cm) | DESCRIPTION                                                                                                                                                                                                                                                                                  |
|---------|------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| O       | 0-3        | Incompletely decomposed layer of litter material. Very fine and fine roots are present. An O <sub>1</sub> horizon of less than 1 cm can be demarcated. Colour is very dark greyish brown, 10YR 3/2. Clear wavy boundary exists.                                                              |
| A       | 3-11       | Layer of organic formation, Texture is sandy loam with granular structure. Fine roots and earthworm are noticeable. Soil is non sticky. Colour is 10YR 3/1, very dark gray. Clear wavy boundary exists.                                                                                      |
| AB      | 11-28      | A relatively large transitional layer. Many very fine roots and fine roots are noticeable. Earthworms are also present. Fine gravels are present. Sandy loam soil with subangular blocky structure. Colour is 10YR 5/6, yellowish brown. Soil is non sticky. Slightly clear boundary exists. |
| B       | 28-87      | Layer of illuviation with evidence of weathering. A large number of colluvial deposits, weathered stones and roots are also seen. About 20% of mottles is observed. Colour is 10YR 5/6, yellowish brown. Smooth and clear boundary exists.                                                   |
| BC      | 87-121     | Transitional layer to the parent material. Structure is subangular blocky and texture is sandy clay loam, with fine gravels present and about 10% mottling. Fine roots are also seen. Colour is 7.5YR 5/6, strong brown.                                                                     |
| C       | 121-       | Colluvial deposits too deep to excavate.                                                                                                                                                                                                                                                     |

All soils have distinct O horizons, although depths tend to decrease with successional development in the order of  $F_0 > F_1 > F_3 > F_6$ . For the woodland ( $F_{17}$ ) site, however, the O horizon is 3 cm thick and is 50% more than that of the  $F_6$  site. The A horizon largely followed the trend of the O horizon, depths ranging from 4.5 to 21 cm and in the descending order of  $F_0 > F_1 > F_3 > F_{17} > F_6$ . Furthermore, the AB transitional horizon is absent only in the new burnt ( $F_0$ ) site. On the other hand, the BC transitional horizon is present on all the soil profiles, while C horizon was not detected in the woodland ( $F_{17}$ ) site despite excavation to 121 cm.

In the early stages of successional development ( $F_0$  and  $F_1$ ), the A horizon is subangular in structure. Further up the chronosequence ( $F_3$ ,  $F_6$  and  $F_{17}$ ), the structure becomes granular. In the subsurface horizons, the structure is either angular or blocky. In addition, roots in the  $F_0$  profile are only confined to the A horizon, while in the other soil profiles they extend to the AB, B and BC horizons.

## Results Of The soil Chemical Characteristics

### (a) Soil Acidity

The soils in this vegetation chronosequence are strongly acidic, pH values ranging from 4.25 to 5.11. Soil reaction tended to increase with depth, and the

highest pH values were recorded for the various C horizons (Figure 3.1a). Along the vegetation gradient, however, the highest pH (4.62) of the O horizon was recorded for the  $F_6$  profile and of the C horizon (5.11) for the  $F_3$  profile. Overall, soils of the early successional communities ( $F_0$ ,  $F_1$ ,  $F_3$ ) are invariably more acidic than the mixed grassland/scrubland ( $F_6$ ), and woodland ( $F_{17}$ ) communities.

The content of exchangeable Al is high in these acidic soils. In the  $F_0$ ,  $F_1$  and  $F_3$  profiles, exchangeable Al decreased with depth being commensurate with pH increase (Figure 3.1b). The lowest values of Al were recorded in either the BC or C horizons of these early successional communities. The soil profiles of  $F_6$  and  $F_{17}$  showed no distinct pattern of Al distribution with depth. The highest concentration of Al was found on the C horizon while the lowest on the B horizon of profile  $F_{17}$ .

In all the 5 soil profiles studied, the value of exchangeable H was consistently lower than that of exchangeable Al (Figure 3.1c). H concentration tended to increase with depth, with the exception of the  $F_3$  profile. Total exchangeable acidity (TEA) closely followed the trend of exchangeable Al which was dominant on the exchange sites (Figure 3.1d). Like exchangeable Al, exchangeable H in the  $F_6$  and  $F_{17}$  profiles showed no discernible pattern with depth.

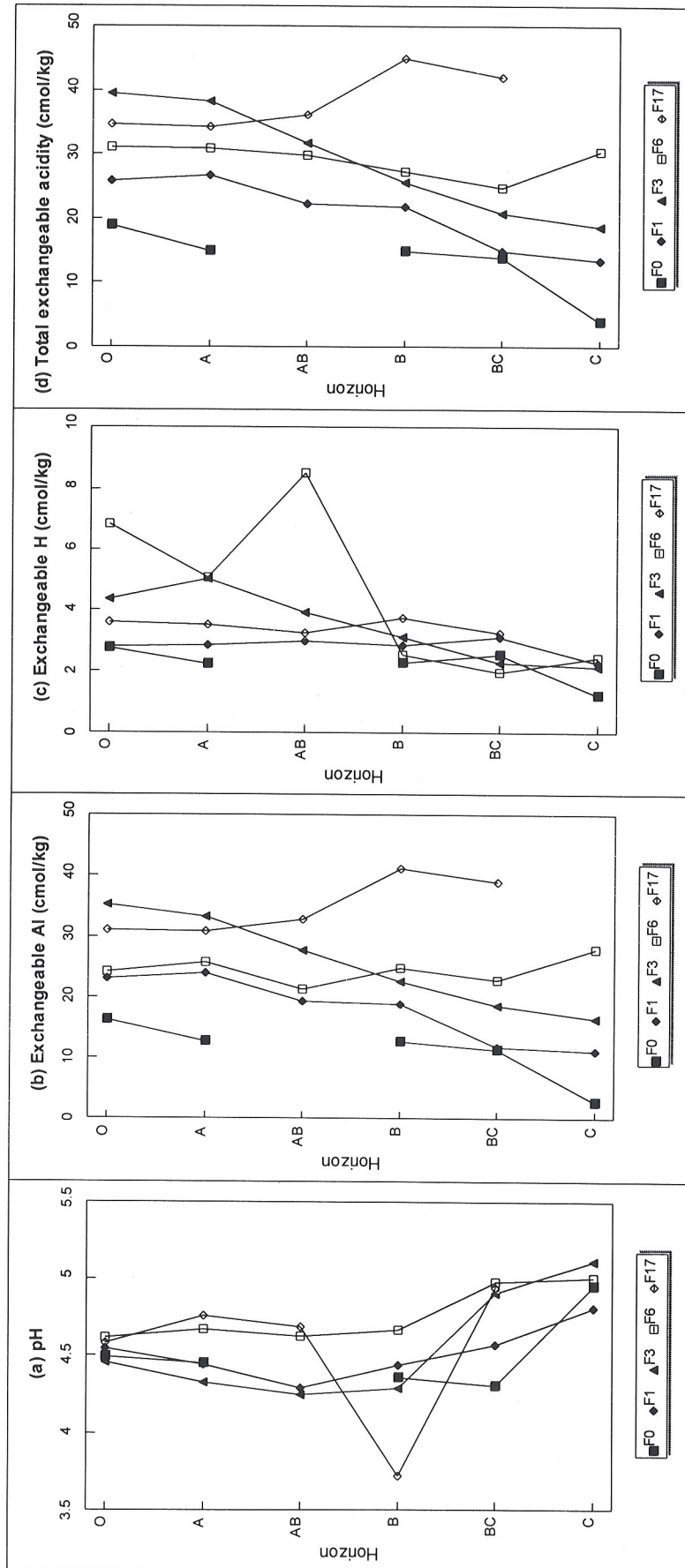


Figure 3.1 - Soil pH, exchangeable Al, H and total exchangeable acidity (cmol/kg) of the soil profiles (Note:  $F_0$  lacks an AB horizon,  $F_{17}$  lacks a C horizon).

On some profile horizons, exchangeable H constituted less than 10% of the TEA, while exchangeable Al varied from 65 to 90%. These results show that exchangeable acidity of these soils is dominated by Al. The Al saturation further confirms the strong acidity of these soils, ranging from 68.9 to 92.3% along the chronosequence. The H saturation varied between 7.7 to 31.1%. The trend of Al and H saturation along the soil profiles was illustrated in Figures 3.2 a and b.

#### (b) Exchangeable Bases

The levels of exchangeable cations K, Na, Ca and Mg in these soils were very low and they tended to vary with depth (Figure 3.3 a to d). Potassium was significantly higher in the O horizon ( $p < 0.05$ ) and decreased gradually and significantly with depth in

all soil profiles.

The pattern of Na distribution along the soil profile is not clear. While the quantity decreased in the A horizon of the  $F_0$  profile, it increased in the A horizon of the  $F_1$ ,  $F_3$  and  $F_6$  profiles. For the  $F_{17}$  profile, there was no significant difference between the O and A horizons. Furthermore, Na content of the A and C horizons of the  $F_3$  profile was not significantly different; it stabilized in the AB, B and BC horizons.

Exchangeable Ca and Mg fluctuated greatly in these soil profiles. In the  $F_0$  and  $F_1$  profiles, Ca and Mg increased significantly with depth ( $p < 0.05$ ), and peaked in the C horizon (Figures 3.3 c and d). In  $F_3$ ,  $F_6$  and  $F_{17}$  profiles, however, Ca content was highest in the O and A horizons and decreased significantly

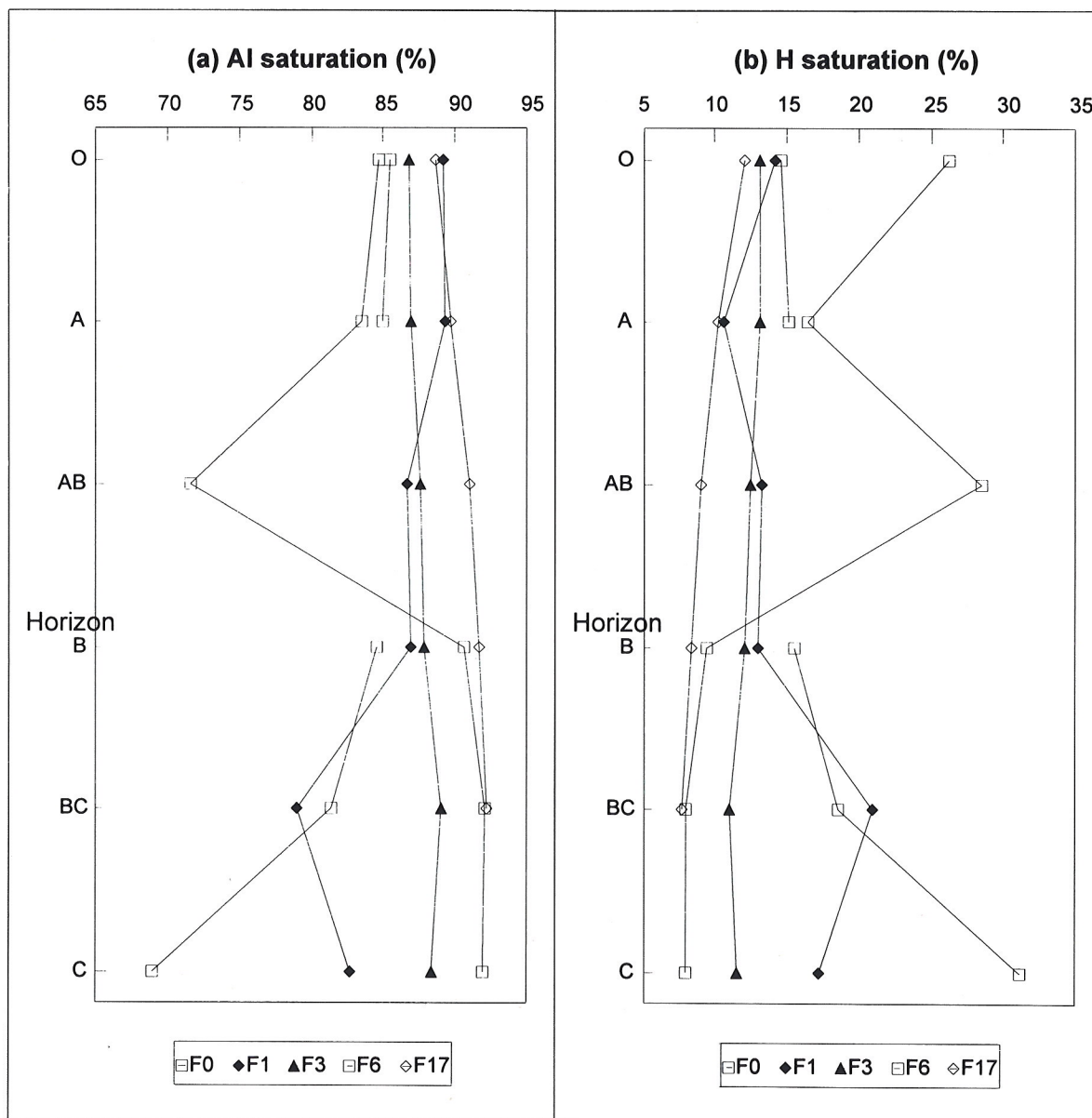


Figure 3.2 - Al and H saturation (%) of the soil profiles (Note:  $F_0$  lacks an AB horizon,  $F_{17}$  lacks a C horizon).



with depth thereafter (Figure 3.3c). Exchangeable Mg in both the O and C horizons were not significantly different, and decreased from the A horizon down the profile (Figure 3.3d). This trend is largely similar for all the soil profiles, except selected layers of profiles  $F_3$  and  $F_{17}$  where there were no significant differences between horizons A and AB. The same observation was found between horizons A and B of the  $F_1$  profile. Likewise, the values of Mg between horizons A, B and BC of profile  $F_0$  were not significantly different at  $p < 0.05$ .

### (c) Soil Organic Matter, Nitrogen And Phosphorus

The distribution of soil organic matter (SOM) and total Kjeldahl nitrogen (TKN) showed a distinct pattern along the soil profiles (Figures 3.4 a and b). They decreased drastically and significantly with soil depth ( $p < 0.05$ ). On the other hand, ammonium-nitrogen showed no clear pattern of distribution with horizons for all the soil profiles (Figure 3.4c). There was little variation in total phosphorus between the soil layers (Figure 3.4d).

### Soil Morphological Characteristics

It is reasonable to assume that within the study area, soil forming factors are almost similar. Although there is considerable variation in altitude between the sites, the soils are of volcanic origin, formed on porphyritic rocks (GASP 1987). Grant (1960) classified the soils in this area as red - yellow podzolic in nature, although Chang *et al.* (1989) preferred to call them yellow earth. Field observation do not support that these soils are red - yellow podzolic. The accumulation of organic matter on the B horizon that is characteristic of podzolic soils and cementation as a result of podzolization were not observed in the field. Furthermore, the ratios of  $SiO_2/AlO_3$  were not determined as these are useful in determining the genesis of soils. An in-depth study of the genesis and classification of these soils will ultimately shed more light on their classification. Field evidence clearly suggest profiles  $F_0$ ,  $F_1$ ,  $F_3$  and  $F_6$  were derived from volcanic rocks while profile  $F_{17}$  represents a typical alluvial formation, overlying the pyroclastic rock. Situated in the valley, the C horizon of the  $F_{17}$  profile was not identified as deep as 120 cm. Alluvial soils are considered juveniles since soil forming processes have not finished developing the profile. On the other hand, this soil could well be a result of debris flow deposits typical of colluvium in valley floors. The actual classification of this soil warrants further research.

The effect of topography on soil genesis has long been recognized (Pregitzer *et al.* 1983, Honeycutt *et al.* 1990). Although the importance of relief is underlined, the vegetation factor is equally important. How does the vegetation cover influence the soils of this study area? Prior to the enactment of the Country Park Ordinance in 1976, fire has been a permanent

agent in shaping the vegetation of this area (Thrower and Thrower 1986, Chau 1994). In chronology, the woodland ( $F_{17}$ ) profile is situated in an area with more than 17 years of fire protection. Profiles  $F_6$ ,  $F_3$ , and  $F_1$  have 6, 3 and 1 year fire protection, while profile  $F_0$  was dug in a new burnt site. A question then arises, will this fire history influence the morphology and properties of these soils? Giovannini *et al.* (1987) reported that an elapsed time of three years was enough to overcome the surficial modification induced in soil by fire. Since their study was carried out in the Mediterranean environment, could this be the case in a humid tropical region like Hong Kong? The surficial depths of the O horizons in these profiles suggest a relationship might exist between vegetation and fire in this vegetation chronosequence. The O horizon is deeper in the early stages of successional development ( $F_0$ ,  $F_1$  and  $F_3$ ) with 6, 5 and 4 cm respectively, which apparently have experienced more repeated burns than the later stages ( $F_6$  and  $F_{17}$ ) which recorded 1.5 and 3 cm respectively. Since one of the indices of horizon identification is soil colour, the role of the deposited ash after fire is not ruled out.

Soil colour is recognized as one of the most obvious and important diagnostic parameters in the description and classification of soils (Coventry and Robinson 1981). It is a physical property that is identifiable in the field, has little or no effect on soil behaviour, but is particularly useful for making a number of meaningful predictions about the soil. Furthermore, it is a guide to the extent of mineral weathering, the amount and distribution of organic matter in the soil, and the state of aeration (Hausenbuiller 1978).

Generally, all the O horizons of the 5 soil profiles exude a very dark gray colour (10YR 3/), except profile  $F_6$  which portrays a black colour (2.5Y 2.5/). This black colour is probably caused by the process of melanization when there was an accumulation of soil organic matter (Harden 1982, Foth 1990). Soil profiles  $F_0$  to  $F_6$  show a decrease from dark to lighter colours down the profile, often portraying a reddish brown colour (5YR 4/) on the BC and C horizons. However, soil profile  $F_{17}$  maintained a strong brown colour on the BC horizon at 121 cm, indicative of incomplete activity of soil forming processes.

### Soil Reaction And Chemical Properties

Soil pH is a good indicator of its chemical status which affects many biological processes including plant growth. Soil pH values in this study area are low, invariably below 5 on all the upper layers. They tended to increase from the BC to the C horizons except profile  $F_0$ . One of the reasons for this increase could be due to the leaching of exchangeable bases downwards the profile. Since the colour of all the soil profiles change from dark to brighter reddish colours with increasing depth, it is fairly safe to assume that dark organic particles which character-

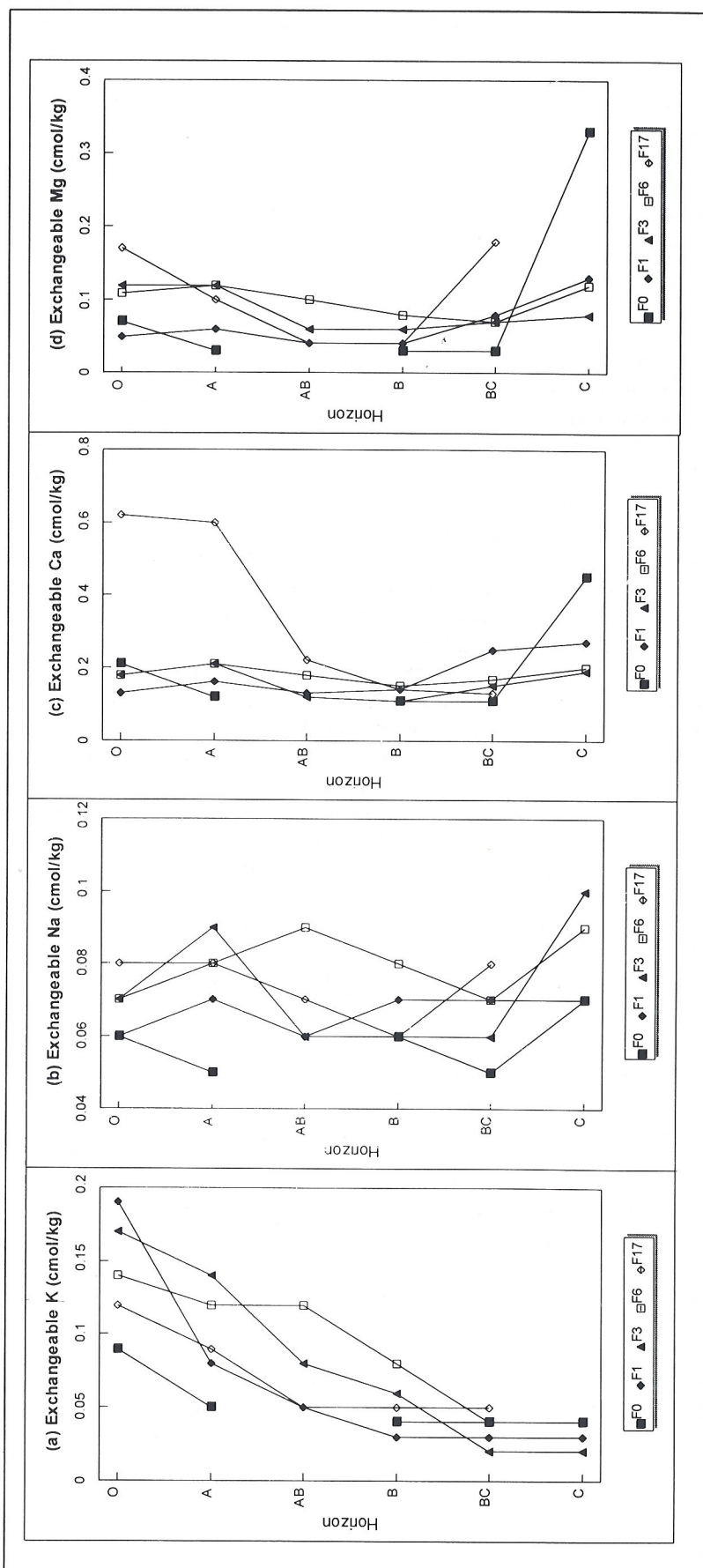


Figure 3.3 - Exchangeable K, Na, Ca and Mg of the soil profiles (Note:  $F_0$  lacks an AB horizon,  $F_{17}$  lacks a C horizon).

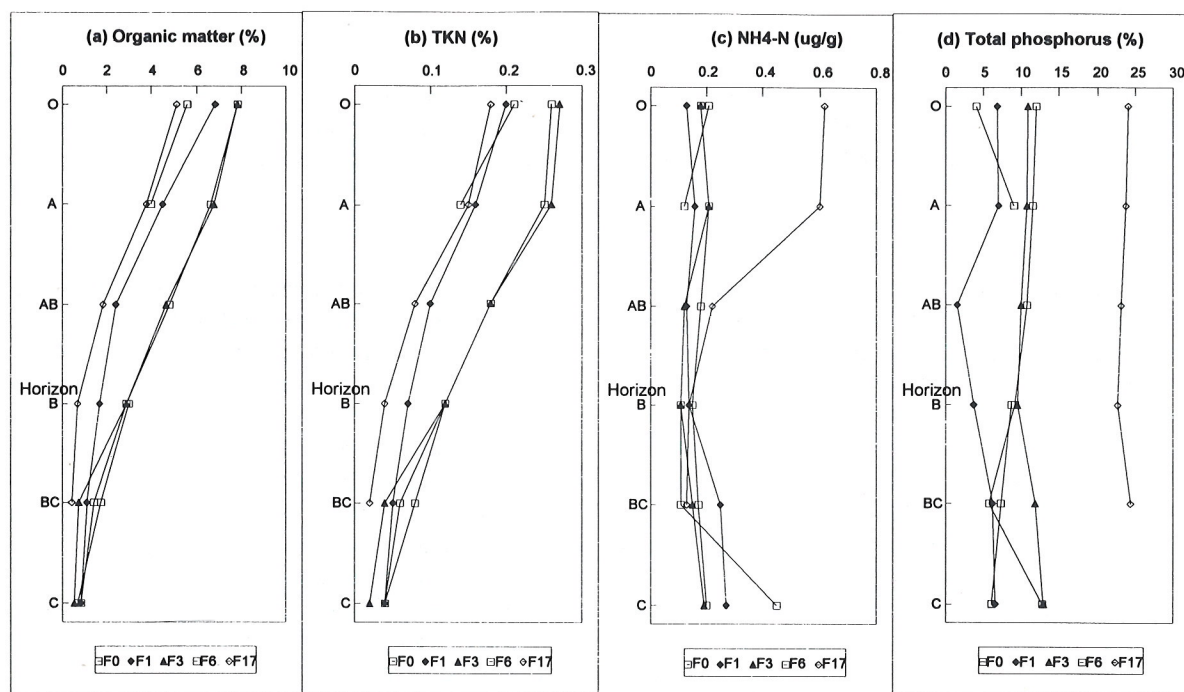


Figure 3.4 - Soil organic matter, TKN, NH<sub>4</sub>-H and TP of the soil profiles (Note: F<sub>0</sub> lacks an AB horizon, F<sub>17</sub> lacks a C horizon).

ize dark colours in the profile also modify the soil pH.

Although soils in this vegetation gradient are generally acidic, there is no clear pattern of distribution in relation to fire occurrence and to successional development thereafter. One common observation, however, is that except the O horizons, the top two horizons (A and AB) of all the soil profiles are more acidic than the deeper horizons (B, BC and C) regardless of the time lapse of fire. Furthermore, since the soil pH of the O horizon of the F<sub>6</sub> and F<sub>17</sub> profiles are lower and significantly different from the A horizons, it is fairly safe to infer that the time after fire and the successional development of vegetation have acted together in making these surface horizons more acidic which is characteristic of the soils in this humid tropical region. Giovannini *et al.* (1987) have also reported that 3 years after fire may be enough to return certain soil properties to prefire levels. These two profiles F<sub>6</sub> and F<sub>17</sub> are located in sites where fire has been absent for 6 and 17 years, respectively.

Al ion accounts for over 65% of the effective cation exchange capacity of these soils. Among the cations, the behaviour of Al deserves special consideration. It is the predominant cation in most acid tropical soils. Being polyvalent, it can be adsorbed strongly by soils, replacing other cations on the exchange sites (Yu and Zhang 1986). It has been reported that there is no single, specific form of Al that controls the availability of Al even within the same soil (Ritchie 1995). Furthermore, Al in the soil solution is a function of both thermodynamics and kinetics, and that the ulti-

mate source may be Al containing minerals, but the pathway of Al before it reaches the solution may involve retention and release by several other solid-phase sinks. Muir and Logan (1982), after assessing the degree of eluviation and illuviation in three Scottish podzols, reported intense leaching of Al in all the profiles studied. In the present study, Al leaching down occurred in profiles F<sub>0</sub>, F<sub>1</sub> and F<sub>3</sub> but not in the grassland/scrubland (F<sub>6</sub>) and woodland (F<sub>17</sub>) profiles.

The content of exchangeable H<sup>+</sup> in these soils constituted less than 30% with most of the samples falling below 10% of the TEA. This clearly shows that the exchangeable acidity in these soils is due almost entirely to monomeric Al<sup>3+</sup> ions, in agreement with findings by Thomas and Hargrove (1984). Generally, exchangeable Al and H tended to be lower in the new burnt site and increased with successional development.

Notable variations in nutrient content were observed along the chronosequence (Figure 3.3). Generally, potassium outweighs other cations in the O layers of all the profiles. The quantity of K tended to build up along the chronosequence in profiles F<sub>0</sub>, F<sub>1</sub> and F<sub>3</sub>, which represent the early stages of successional development. This buildup declined as succession advances to the grassland/scrubland (F<sub>6</sub>) and woodland (F<sub>17</sub>) stages. The decrease of K with depth could be due to leaching, while the changes along the chronosequence is most likely a result of the time lapse after fire and of uptake by biomass in later stages of successional development. Besides, K is uptaken by vegetation in excess of its requirement. No clear pat-



tern is observed in the distribution of Na.

The content of calcium is equally high in the upper and lower horizons. For profiles  $F_0$  and  $F_1$  peak accumulation occurred in the C horizon (0.45 and 0.027 cmol kg<sup>-1</sup>), and for profiles  $F_3$  and  $F_6$  in the A horizon which have 0.21 cmol kg<sup>-1</sup> respectively. Similarly, more Ca accumulates in the O, A and AB horizons of the woodland ( $F_{17}$ ) site, which is likely a result of pumping of this element by tree roots from the C horizon to the top layers. A similar trend was also observed for profiles  $F_3$  and  $F_6$ , possibly due to the established fibrous root system of the grassland vegetation. This root system concentrates in the A horizon. Furthermore, the higher concentration of Ca on the C horizons could also be as a result of leaching. The pattern for Mg was less conspicuous, although the element tended to decrease in the B horizons of these soil profiles.

The addition of organic matter to the soil by plants and animals can be regarded as the most important factor in soil formation (Curtis *et al.* 1976). Soil organic matter concentration usually decreases rapidly with depth (Jenkinson 1988). From Figure 3.4a, it is clear that the O horizons accumulated more organic matter than all other layers. Soil organic matter was highest in the grassland ( $F_3$  and  $F_6$ ) sites. The variation in soil organic matter content testifies the fact that decomposition and humification of plant materials vary with plant species (Kumada 1987), organisms, as well as soil conditions. Since soil conditions in these sites are largely the same, the difference in vegetation cover is probably the main reason accounting for the variability in soil organic matter. The kind of vegetation involved in soil development and the amount of plant residue added each year are key factors in determining the extent and pattern of organic matter accumulated in soils (Hausenbuiller 1978). The predominantly grass species contribute a large amount of litter due to annual die-back of the above-ground portion and roots, resulting in the accumulation of organic matter. On the other hand, the microclimate conditions in the woodland site are more favourable to mineralization resulting in lower soil organic matter compared to the grassland sites.

The bulk of soil N occurs in organic combination, principally as resynthesized substances formed during the decay of plant and animal residues. It is therefore normal that total N content followed closely the pattern of soil organic matter (see Figure 3.4b) being highest in the O horizon of profiles  $F_3$  and  $F_6$ . Although total N content of these soils differ significantly, it provides little information about the N-supplying capacity of the soils. One reason is that the release of N in available form through mineralization varies from site to site. The lack of nitrate in these profiles is probably caused by leaching, plant uptake, low nitrification in the soil and immobilization of microbes.

NH<sub>4</sub> ranged 0.42 to 22.85 µg g<sup>-1</sup> and no discernible pattern was observed between the soil profiles (Figure 3.4c). Despite this the highest quantity was found in the O horizons of profiles  $F_0$ ,  $F_1$  and  $F_3$ . For profiles  $F_6$  and  $F_{17}$ , the A horizons yielded the highest values.

## Conclusion

The macromorphological characteristics and chemical properties of the 5 soil profiles have been presented. In addition to the natural factors of soil formation, it is clear that anthropogenic factors also prevail.

As in most tropical soils, distinct soil horizons are identified on each of the soil profiles viz. the O, A, B and C horizons. However, the C horizon was not identified in profile  $F_{17}$  located at the valley of Tai Mo Shan. Transitional soil layers of AB and BC are found on all the soil profiles, except profile  $F_0$  where the AB horizon was absent. The O horizon of all the profiles is very dark to black in colour, and never exceeds 6 cm in depth, while the A horizon ranged from 4.5 to 21 cm.

Since the soil colour of the O horizon is either very dark or black, the deposited ash particles might have influenced the formation of this O horizon. Exchangeable K tended to accumulate closer to the top horizons which may be related to its availability in the deposited ash content. Exchangeable Al was lesser in the new burnt site and tended to be low in the early successional stages. The levels of SOM and TKN were higher in O horizon than other horizons.

Al is the dominant exchangeable cation in these soils, which is commensurate with the high acidity. The content of exchangeable Al varied along the vegetation gradient, being consistently higher in the woodland ( $F_{17}$ ) site and lowest in new burnt ( $F_0$ ) site.

For total nitrogen and soil organic matter content, the predominantly grassland sites (e.g.  $F_1$ ,  $F_3$ ) recorded higher values on the surface horizons than from the woodland ( $F_{17}$ ) site.

The depth of the O horizon decreased with successional development of the vegetation after fire in the order of  $F_0 > F_1 > F_3 > F_{17} > F_6$ . The A horizon showed a similar trend. It is therefore clear that the effect of fire is more prominent on the top two soil horizons. Since the study of the genesis and classification of these soils have not been undertaken, it is rather questionable to identify these soils as red-yellow-podzolic. However, this nomenclature is acceptable pending a study that will prove otherwise.

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## Hong Kong Landform Series, No. 4

# Ripple Bedforms and Lamination in the Littoral Zone

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### Introduction

Landforms develop on a variety of scales, ranging from the smallest sediment accumulations to global features such as abyssal plains on ocean floors. A variety of small-scale morphological features may develop along the sediment/water interface wherever water velocities are sufficient to move sediment grains. These "bedforms" are strongly controlled by parameters such as grain size, flow strength, flow direction and water depth. They include a large variety of shapes and sizes and include features such as ripples, dunes, antidunes and plane beds. This landform article concentrates on the variety of types, characteristics and origins of ripple bedforms. Two major types are commonly distinguished: current ripples and oscillatory ripples.

### Current Ripples

Current ripples are asymmetric small scale bedforms (Figure 1) that develop in response to unidirectional flow, and are restricted to sediments with a grain size of less than about 0.7 mm (Leeder, 1982). The up-current direction is gentle and referred to as the stoss side, whereas the downstream direction is steep (30-35°) and called the lee slope (Figure 1A). Typical values for ripple heights range from 0.5 to 3 cm, while wavelengths vary from 5 to 40 cm. Ripple indices (wavelength:height ratios) are commonly 10-40 (Allen, 1968). Ripple size increases with bed shear stress. A rough relationship also occurs between wavelength and grain size, with the latter being about 1000x grain diameter. Allen (1968) proposed a classification of ripples based on the form of the ripple crestline in plan view. This may be straight, sinuous, lunate or linguoid (Figure 1E) and adjacent ripples may be "in phase" or "out of phase" with one another. In general, there is an increasing complexity as flow velocity increases for any given water depth, and a transition from straight, through sinuous to linguoid or lunate types also occurs (Figure 1E) (Boggs, 1987). In profile, ripples show small scale cross-lamination. This may not be visible in sediments of uniform colour and size mineral composition, as is common in Hong Kong. Where strongly contrasting dark and light coloured minerals are present (often of varying densities), wave sorting separates the different mineral suites and enhances the visibility of internal laminations. This is the case at Tong Fuk, Lantau Island. There, hornblende weathered from local volcanic rocks

makes planar cross-lamination in beach deposits and ripple bedforms easier to see in profile (Plate 1, D and E). Two main types of cross-lamination may be generated by ripples, depending on the nature of the crestline. Where the crest is straight, planar cross-lamination will develop (Figure 1B). In contrast, sinuous to linguoid ripples will produce trough cross-lamination, as they migrate across scoured depressions on the lee side of the ripple. Where there is rapid deposition of sediment during the formation of ripples, the ripple forms will "climb" over one another in "sets" as shown in Figure 1 (B and C) (Allen 1972). Where sandy sediment is sparse, as on mudflats, isolated ripples may occur, which give rise to "flaser bedding" in cross section (Selley, 1975) (Figure 1G).

A variety of indices have been proposed in order to describe ripples (Gardiner and Dackombe, 1983). These include: the ripple index (RI) = wavelength/height, and the ripple symmetry index (RSI) = length of the stoss side/ length of the lee side. When these parameters are plotted against each other, current and oscillation, as well as wind-generated ripples, plot in different parts of the resulting graph (Figure 1D) (Tanner, 1967).

### Oscillation Ripples

Wave generated (oscillation) ripples are laterally persistent and often bifurcate. Size is highly variable, since their formation depends on the scale of the surface water waves. Wavelengths typically range from 9 cm to 2 m and heights are between 0.3 and 25 cm. The ripple index is commonly 4-13 (Leeder, 1982) and ripple crests lie parallel to the wave crests.

Oscillation ripples develop in response to grain movement caused as waves pass by. As a wave crosses a particular location it sets up a circular motion in the water column. The orbit of this circle becomes ellipsoidal with increasing depth, in shallow water. Close to the sea/lake floor, a "to and fro" motion develops in the water that transports particles towards the ripple crests. This causes chevron lamination to develop within the sediments (Figure 1F).

Close to locations of breaking waves, there is an overall net landward transport of sediment (Leeder, 1982) superimposed on the wave-induced patterns. This produces "wave-formed current ripples" (Figure 1F; Plate 1C), with similar cross laminae to those of current ripples. They may be distinguished from current ripples by their ripple index (generally < 15, com-



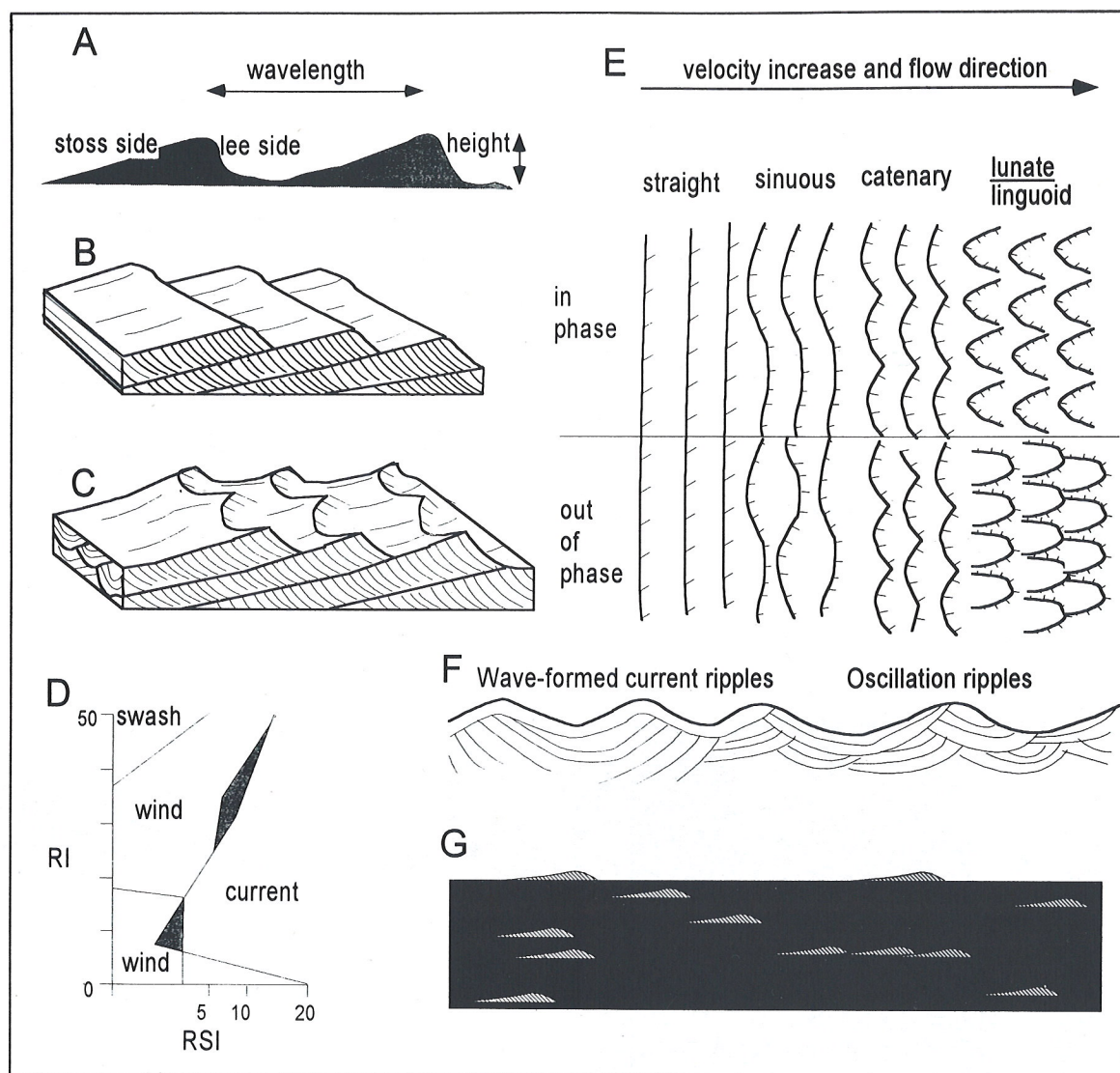


Figure 1 - Major characteristics of ripple bedforms. A: descriptive terminology; B: planar cross-lamination developing for straight-crested ripples; C: trough cross-lamination developing for catenary ripples; D: relationship between ripple index (RI), ripple symmetry index (RSI) and environment of formation. Shaded areas represent overlap in data; E: Classification of ripples in plan view; F: lamination style for wave-formed current ripples and oscillation ripples; G: flaser bedding developing in a sand-poor mud environment. Diagrams modified from Leeder (1982), Selley (1976) and Gardiner and Dackombe (1983).

pared with values of up to 40 for current ripples), and by the occasional presence of crest bifurcation (rarely present for current ripples). The dominant ripple indices at the Tong Fuk tidal flat range between 6.5 and 10 (Tam, 1993) indicating that the ripples there are dominantly of the wave-formed current type.

Ripple bedforms are visible along most shorelines where silts and fine to medium sands dominate the sediments. However they are often best exposed on relatively coarse-grained tidal flats. The Tong Fuk tidal flat (8101 8092) provides excellent examples of a variety of ripple types at low tide. Other coasts with good examples of shallow water ripples occur just off Repulse Bay (8385 8108) and at Tai Long Wan (8559 8305).

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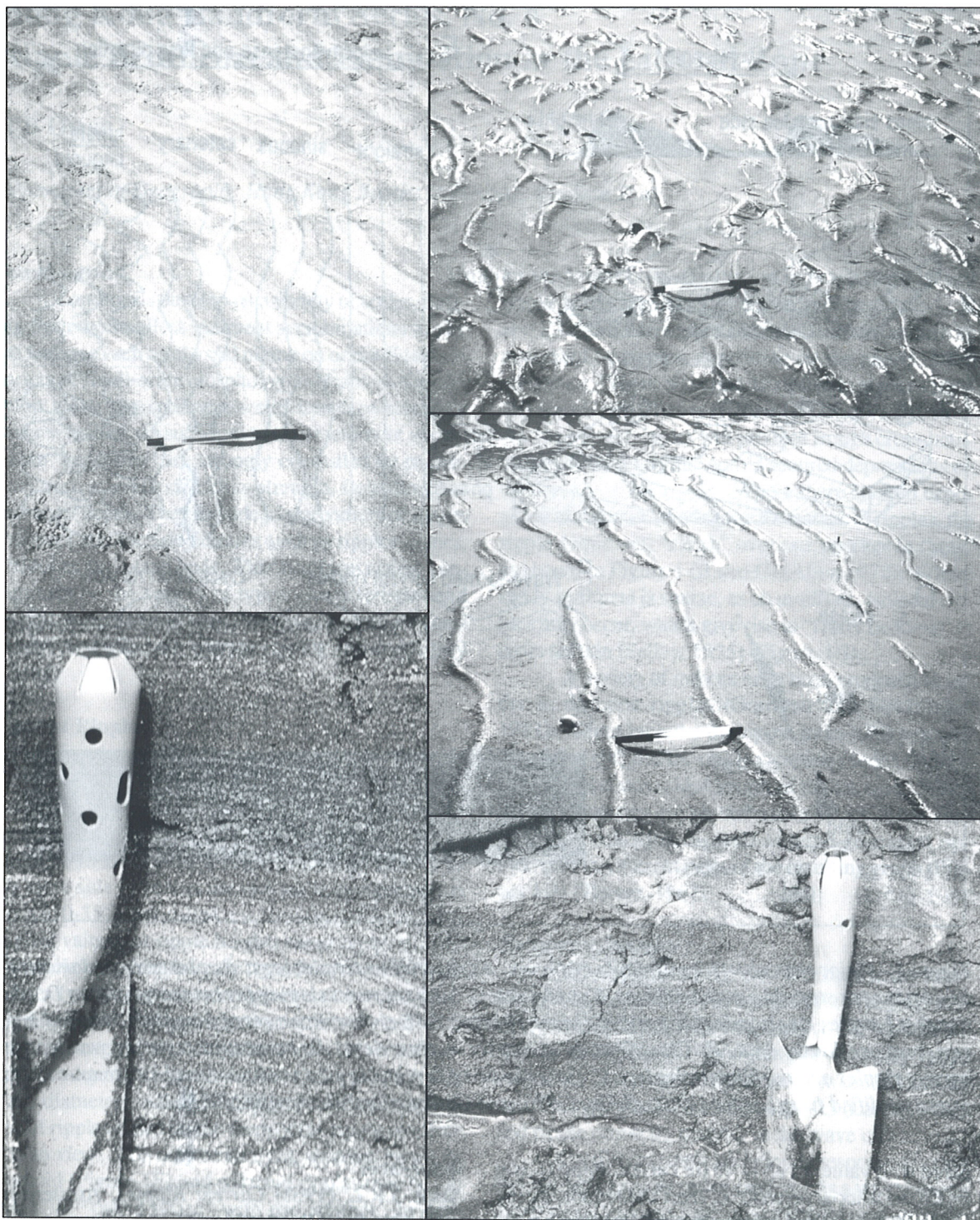


Plate 1 - Ripple bedforms developing at the Tong Fuk tidal flat, Lantau Island. A: sinuous current ripples showing distinct separation of sand (light shade), at the base of the lee side, and finer silt (dark), on the stoss side. Current direction is from right to left. B: out of phase sinuous to catenary current ripples. Current direction from right to left. C: wave-formed current ripples showing straight to sinuous crests. Slight current from left to right. D: planar lamination developing in upper tidal flat to beach zone as a result of swash processes. E: patchy planar lamination developing in upper tidal flat zone. Note light shaded sand in low points between ripples, at the surface. These give rise to the thin discontinuous sands in the profile.

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