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A STUDY OF THE WEATHERING OF THE BUKIT TIMAH GRANITE PART A : REVIEW, FIELD OBSERVATIONS AND GEOPHYSICAL SURVEY

ÉTUDE DE L'ALTÉRATION DU GRANITE DE BUKIT TIMAH (SINGAPOUR) 1re PARTIE : BIBLIOGRAPHIE, OBSERVATIONS DE TERRAIN, ÉTUDES GÉOPHYSIQUES

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Abstract

The Bukit Timah granite exhibits a full range of weathering grades. Examination of these exposures shows that the weathering has been rapid. Field observations and geophysical surveys show that the rock has been weathered up to 70 meters depth, and that the main mechanism of weathering is chemical decomposition. The humid tropical condition in Singapore with high annual precipitation has produced secondary weathering of the residual soil. The weathering profiles suggest that the weathering of the Bukit Timah granite is stratified with weathered layers and a sharp boundary between the residual soil and the slightly to moderately weathered granite.

This paper (Part A) is a review of current weathering classification systems for weathered rock. Some results from field observations and geophysical surveys are also presented in the paper. A weathering classification and determination method is proposed for the Bukit Timah granite. Results from field and laboratory investigations of the weathering of the granite and material properties will be presented in Part B.**

Résumé

Le granite de Bukit Timah présente toute une gamme d'états d'altération. L'examen montre que l'altération a été rapide. Les observations sur le terrain et les études géophysiques montrent que la roche a été altérée jusqu'à 70 mètres de profondeur, le principal mécanisme de l'altération ayant été la décomposition chimique. Les conditions tropicales humides de Singapour avec une pluviométrie très forte ont produit une altération secondaire du sol résiduel. Les profils d'altération suggèrent que l'altération du granite de Bukit Timah est stratifiée avec des niveaux altérés et une limite brutale entre le sol résiduel et le granite légèrement ou modérément altéré.

Cet article (1re partie) présente d'abord une bibliographie des différents systèmes de classification des roches altérées. Ensuite sont présentés des résultats des observations de terrain et des études géophysiques. Une classification en termes d'altération est proposée. Les résultats des études détaillées de terrain et de laboratoire sur les facies altérés du granite et leurs propriétés seront présentés dans une seconde partie.**

Introduction

Weathering of rock caused by physical disintegration and by chemical decomposition affects the physical and the mechanical properties of both the rock material and of the rock mass. Physical disintegration involves the mechanical breakdown of the rock mass (usually controlled by discontinuities in the mass) and of the rock material (controlled by micro-discontinuities such as grain boundaries and mineral cleavages). Chemical decomposition affects almost all minerals; only a few, notably quartz, are more or less unaffected. The processes involved in decomposition are oxidation, reduction, hydration, hydrolysis, carbonation and solution.

Under temperature humid climatic conditions, decomposition and disintegration occur simultaneously and it is difficult to separate the direct effects of the two processes. Their relative importance is very much a function of the climate (Peliter, 1950; Thomas, 1974; Fookes, 1991). In Singapore, decomposition is far more effective than disintegration (Zhao *et al.*, 1992). A third group of processes is also recognized as the biological weathering. The organic matter from animals and plants react with the rock mass and cause further decomposition of the rock.

The rate at which the various weathering processes takes place depends mainly on the following three factors :
a) environmental, dominated by the climate, but also involved are topography, the hydrological conditions and the biological systems are important;
b) the properties of rock mass, especially the homogeneity, and the nature, spacing and pattern of the discontinuities, i.e., the macrofabric;
c) the properties of the rock material, including composition, fabric, texture and permeability.

At present, the weathering classification system initially proposed by Fookes *et al.* (1971) and modified by Dearman (1974, 1978) is widely used (e.g., Fookes *et al.*,

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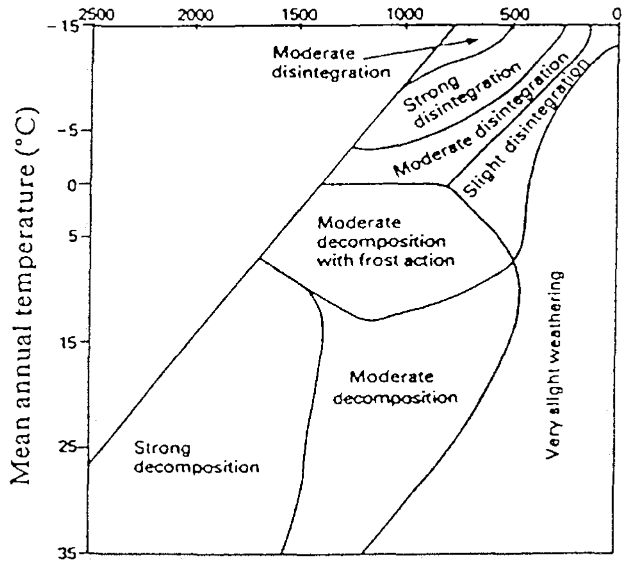


Fig. 1 : Relationship between climate and type of weathering (after Fookes *et al.*, 1971).

1971; Baynes *et al.*, 1978; Forth and Platt-Higgins, 1981; Hencher and Martin, 1982; GCO, 1988; Lee and de Freitas, 1989), where the granitic rocks are divided into six grades from fresh rock (Grade I) to residual soil (Grade VI). The classification of the rock mass and of the rock material is with respect to fabric and colour, strength index, fracture spacing index, rock quality designation (RQD), rock/soil ratio, elasticity, porosity, and micro-indexes (micropetrographic and microfracture).

Relationship of rock weathering and climate

The main factors which govern the weathering of rocks are the climatic and the geographic conditions during the weathering, the composition of the source material, the groundwater condition, and the period of time over which weathering have been active. The weathering processes as affected by the climate has been studied in the past by Peliter (1950), Iliev (1967), Sanders and Fookes (1970), Farjallat *et al.* (1974), Onodera *et al.* (1974), Wilson (1975), Baynes and Dearman (1978a, 1978b, 1978c), Baynes *et al.* (1978), Irfan and Dearman (1978a, 1978b), Saito (1982), Cawsey and Mellon (1983), Ollier (1984), Beavis (1985), Martin (1986), Dearman *et al.* (1987), Fookes (1991), Malone *et al.* (1992), Zhao and Broms (1993).

The climate effects the weathering both directly and indirectly (Peliter, 1950; Ollier, 1984; Saito, 1981). Temperature governs the rate of the chemical reactions, but frost action, heating and cooling are important which can cause physical disintegration of the rock. Chemical decomposition is important in a hot and humid climate, and of particular importance is the solution of silica.

The chemical weathering depends both on the rainfall (frequency and duration) and on the temperature. The reaction rate doubles or triples for every 20°C increase of the temperature (Saito, 1981). Rainforest in the tropics are subjected to heavy rainfall, so that cracks and other voids in the rocks and in the soils are filled with water even close to the ground surface. The pH value is typically low between 3.5 and 5.5, due to the rapid weathering of the soil areas with a hot and humid climate. The sodium, potassium, magnesium and calcium content of the residual soil is low (Ollier, 1984).

The relative importance of the various weathering processes for different temperature and rainfall conditions is shown in Fig. 1. It can be seen that the main weathering mechanism in Singapore is chemical decomposition.

The chemical weathering of granite in humid tropic regions

The chemical reactions involve such aggressive atmospheric agencies as water, oxygen and carbon dioxide which affect the quartz, the alkali feldspars, the plagio-

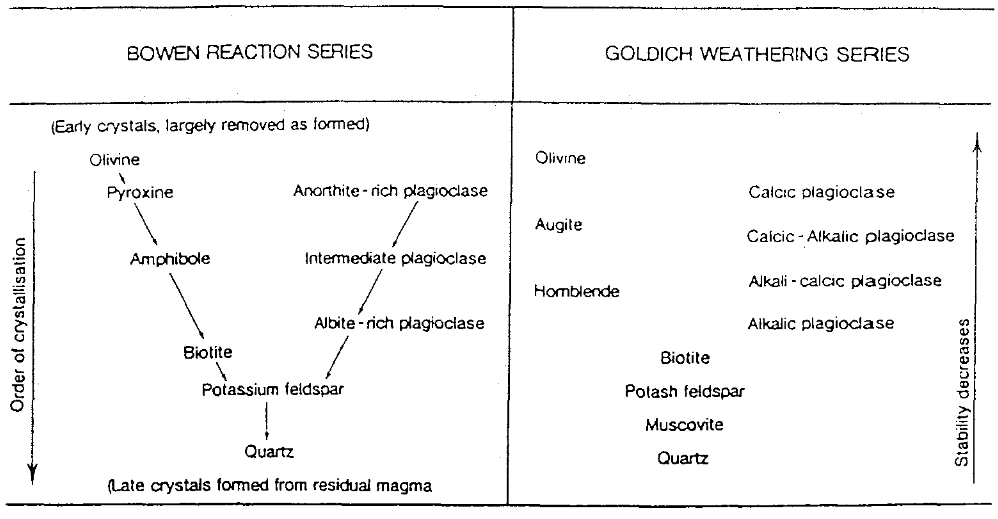


Fig. 2 : The weathering series of Goldich and the reaction series of Bowen.

$$KAlSi_3O_8 + H^+ \rightarrow K^+ + AlSi_3O_8^- + SiO_2 + H_2O$$
Orthoclase (decomposition in acidic solution)

$$NaAlSi_3O_8 + H^+ \rightarrow Na^+ + AlSi_3O_8^- + SiO_2 + H_2O$$
Na-Plagioclase (decomposition in acidic solution)

$$CaAl_2Si_2O_8 + H^+ \rightarrow Ca^{2+} + Al_2Si_2O_8^{2-} + SiO_2 + H_2O$$
Ca-Plagioclase (decomposition in acidic solution)

$$KAl_2(Si_3AlO_{10})(OH)_2 + H^+ \rightarrow K^+ + Al^{3+} + AlSi_3O_{10}^{4-} + SiO_2 + H_2O$$
Muscovite (decomposition in acidic solution)

$$K(Mg, Fe)_3(Si_3AlO_{10})(OH)_2 + H^+ \rightarrow K^+ + (Mg^{2+}, Al^{3+}) + AlSi_3O_{10}^{4-} + SiO_2 + H_2O$$
Biotite (decomposition in acidic solution)

$$Mg_2SiO_4 + H^+ \rightarrow Mg^{2+} + SiO_2 + H_2O$$
Olivine (decomposition in weak acidic solution)

Fig. 3 : Chemical reaction and weathering of silicate and some typical igneous minerals.

clase feldspars and the micas in the granite. The chemical weathering of the granite in a hot and humid climate can be intensive. Quartz usually remains unaltered, but feldspars are often converted into kaolinite and micas into various clay minerals (Wilson, 1975; Cawsey and Mellon, 1983). The decomposition products are clay minerals, insoluble iron oxides and hydroxides, and cations and silica in solution (Ollier, 1984). The nature and the relative proportions of the weathering products depend on the rate at which soluble materials are flushed out of the system. The different clay minerals can only develop if the cations essential to the formation of the mineral are present within the micro-environment. If only small amounts of cations are flushed out of the system, cation-rich species such as montmorillonite and illite are formed whereas intensive flushing, or continued weathering, results in the complete loss of all but the most insoluble materials and kaolinite, and then gibbsite are produced (Baynes and Dearman, 1978a).

Based on early weathering studies, Goldich (1938) has presented a weathering sequence for the common igneous minerals (Fig. 2). He pointed out that the weathering sequence is the reverse of Bowen's reaction series which lists minerals in their order of crystallization. However, the weathering series can also be related to 'basicity', the ratio of silica and the other cations. The weatherability of rock increases with increasing content of cations which can be replaced by hydrogen.

The weathering of silica in the form of quartz and silica minerals is generally insignificant. However, feldspars and micas are affected by the weathering. The basic unit of silicate minerals is the silicate tetrahedron where the silica atom is located at the centre of four oxygen atoms. The tetrahedra are arranged in discrete groups, chains, sheets, or three-dimensional structures. However, the Si-O-Si linkages are not very strong, and the stability is maintained by the complex interplay of geometrical and electrostatic factors. Feldspars are a group of alumino-silicate minerals and micas are basic aluminium silicates with a sheet structured crystal lattice. During the weathering of the silicates the cations are replaced by hydrogen ions. If M represents the metal ions and SiO represents the silica groups, the simplest expression of

Table 1 : Classification of weathered crystalline rocks (after Irfan and Dearman, 1978a).

Weathering class	Grade	Description of rock material and rock mass	Strength	Index properties RQD (%)	Rock/soil (% rock)	Effective porosity
Fresh	I	No visible sign of material weathering. Near boundary with Grade II some slight discolouration on major defects	Very high	Very high 90-100	95-100	
Slightly weathered	II	Discolouration indicates weathering of rock material and defect surface Discolouration ranges from defect surface only to completely stained	Very high to to 50-60% of fresh rock strength	75-90	90-95	5% increase from fresh rock
Moderately weathered	III	Less than 50% of material decomposed and disintegrated to intact soil. Rock core discoloured and weakened	30% of fresh rock strength	40-75	60-90	7% increase from fresh rock
Highly weathered	IV	More than 50% of material decomposed and disintegrated to intact soil. Rock core discoloured and weakened	15% of fresh rock strength	10-40	30-60	10% increase from fresh rock
Completely weathered	V	Intact friable soil which may be weakly cohesive. Soil has fabric of parent rock	Extremely low	0-10	0-30	20% increase from fresh rock
Residual soil	VI	Friable soil with original rock fabric completely destroyed	Extremely low	0	0	> 20

chemical weathering of the silicate minerals is (Ollier, 1984) :

$$MSiO + H \rightarrow M + HSiO$$

silicate + hydrogen → metal cation + silicon hydroxide

Detailed chemical reactions during the weathering are presented in Fig. 3 for various minerals.

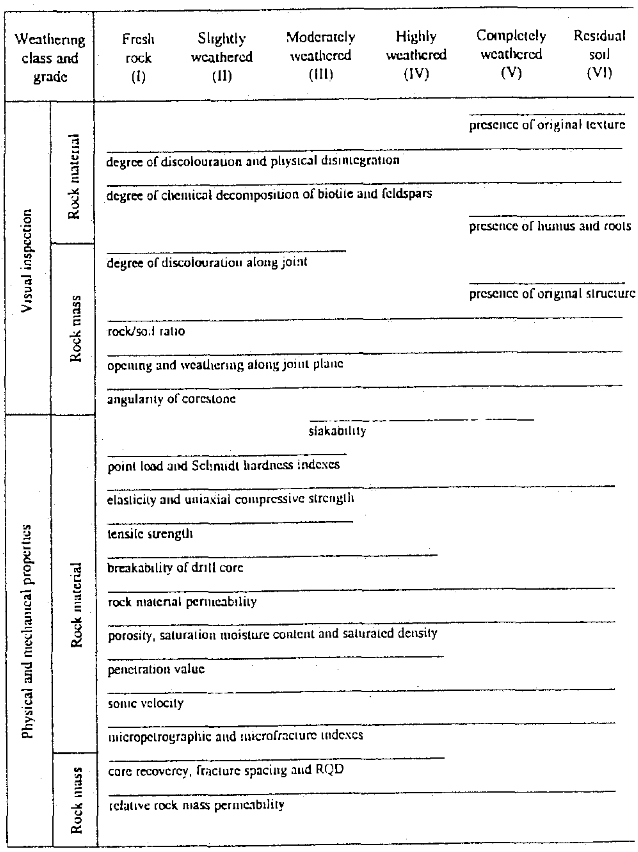
Classification of weathered granite

The classification of weathered rocks for engineering purposes should be based on characteristics of the rock which can be determined in the field, or in the laboratory. Classification methods range from those which are based purely on visual inspection, thus subjective, to those based on the results of precise and detailed testing. Generally used classification systems are based on characteristics which can be determined by visual inspection and by a number of relatively simple index tests. Methods frequently used to evaluate the degree of weathering are presented in Table 1.

The most frequently used rock classification system is that developed by Fookes *et al.* (1971) and later modified by Dearman (1974, 1978). This classification system was initially developed for the granitic rocks from Dartmoor, southwest England. The authors warns against its use for other than granitic rocks. However, geologists and engineers have applied this classification system to all kinds of rock, in different parts of the world. The classification shown in Table 1 can be used for granitic and crystalline metamorphic rocks.

There are few problems with the recognition of fresh rock, and of completely weathered rock. The separation of Grades II, III and IV can be difficult. However, for the classification of weathered rocks for engineering purposes, the following criteria should be used :
a) description of rock, including colour, texture and rock/soil ratio (material and mass);
b) slakability (material);
c) strength indexes, including Schmidt hammer index, point load index, uniaxial compressive strength and modulus of elasticity (material);
d) porosity (material);

Table 2 : Popular methods used to define the weathering grades of granite. (The length of the line drawn above the name of each method describes the effective range of use.)



e) fracture spacing index and rock quality designation (RQD) (mass);
f) relative rock mass permeability (mass);
g) micro-indexes, including micropetrographic index and microfracture index (material).

Description of rock material and rock mass

The description of rock and rock mass is essentially by visual recognition. The character and the range of use are described in Table 2.

Degree of discolouration : This diagnostic feature is used to classify the weathering of the rock material and of the rock mass. Discolouration is only one of several phenomena which can occur when chemical decomposition commences. For example, in the Bukit Timah granite, discolouration along the existing joints is extensive and widely distributed, which indicates the strong chemical weathering and the presence of groundwater.

Degree of chemical decomposition : Specific terms have been proposed such as 'gritty' and 'clayey' to define the degree of weathering of feldspars (Irfan and Dearman, 1978a). The effects of chemical weathering are usually visible, and these terms are adequate to describe the decomposition of granitic rocks.

Degree of physical disintegration : Specific terms have been provided such as 'opening up of grain boundaries' and 'intensive microfracturing' to describe the effects of physical weathering (Irfan and Dearman, 1978b). In granite, the effects of physical weathering are generally easy to recognize. Grain boundary conditions and degrees of microfracturing can be described using the terms suggested by Irfan and Dearman (1978b).

Presence of original texture and structure : The description of the original texture and of the structure can be used to distinguish between Grade V and Grade VI in the weathering classification scheme. If the original texture (of material) and the structure (of mass) are present, a granite should be classified as Grade V or better. If they are absent the granite is referred to as a residual soil (Grade VI). With this concept granitic rocks of Grade V can be separated from those of Grade VI.

Presence of humus and roots : It has been suggested that the presence of humus and roots can be used to distinguish rocks of Grade V from those of Grade VI (Little, 1969). The rock becomes a residual soil (Grade VI) if humus and roots are present. The rock remains Grade V if they are absent. However, this criterion may not be applicable to all residual soil as some residual soils do not contain humus and roots.

Rock/soil ratio : It has been recognized than the ratio of rock to soil in weathered crystalline rock is an index of weathering Grade (Table 1). This ratio often refers to the percentage of corestone in a rock mass, and it is possible in the field to determine this ratio as well as from core logs. This ratio is an essential index in the weathering classification of the granitic rocks, espacially in the separation of Grades III, IV and V. However, recent studies indicated that the rock/soil ratio is not sufficient to describe the engineering properties of a rock mass. A better index is needed based on the weathering grades of the corestone and of their surrounding soil (Lee and de Freitas, 1989).

Slakability of rock material

The slake durability test is a common mechanical test method to identify the particular grade of weathered rocks. It is used by many to define the boundary between Grades IV and V. If the specimen disintegrates in water the material is either Grade V or VI. If it does not disintegrate it is Grade IV or better. However, it has been suggested that slake durability should be used only as a classification test, and that the results must be interpreted in terms of the petrography of the rock since the test does not incorporate any aspects of decomposition, as is distinct from physical disintegration.

Strength indexes of rock material

The strength, hardness and modulus of elasticity decrease during the weathering of rocks. It is thus expected for a particular granite that an increase in the degree of weathering will result in a progressive reduction of the strength. As indicated in Table 1, the strength index is one of the most important criteria in the classification of the weathering grade.

Schmidt hardness index : Schmidt hammer is widely used to determine the *in situ* hardness and the strength of rocks, and is a very rapid method. However, it should be noted that the Schmidt hardness index is only applicable to fresh (Grade I) and slightly weathered (Grade II) rocks, and perhaps to Grade III rock. For weathered rocks of Grades IV, V and VI, the hardness is too low to be meaningful.

Point load index : The point load index has proven to be an extremely useful and reliable index for determining the relative strengths of weathered rocks in the field, provided a large number of tests are made, since the point load strength is related to the weathering grade. The test, however, is of little value when the point load index is smaller than 0.1 MPa.

Uniaxial compressive strength : Weathering cause an immediate, and often large reduction of the compressive strength of rocks. For high strength rocks, such as granites, the loss between fresh (Grade I) and moderately weathered (Grade III) can be as high as 70 %. When weathering proceeds beyond Grade III, the relative strength loss is relatively small. The weakening and breaking of bonds between mineral grains, and the development of microfractures, are thus characteristics of the transition from Grade II to Grade III.

Elasticity of rock material

The fracturing which accompanies weathering, and the replacement of brittle minerals by soft clays, result in a significant reduction of the modulus of elasticity (Beavis, 1985; Baynes *et al.*, 1978). It has been noted that with increased weathering, the modulus of elasticity decreases linearly with decreasing uniaxial compressive strength (Irfan and Dearman, 1978a).

Sonic velocity

The changes of the modulus of elasticity and the porosity of the rock material and of the rock mass can be reflected in the changes of the sonic velocities, since the velocities are functions of the modulus of elasticity and of the porosity. A velocity index (Iliev, 1967), which gives a quantitative index of degree of weathering of rock material, has been proposed for granites. This index is useful laboratory determination of the weathering (Dearman *et al.*, 1987).

Penetration test

The depth of penetration of a penetration test is related to the hardness and the strength of the rock material (JSCE, 1980). A simple penetration test, therefore, can provide a useful index on the strength which can be used for the classification of rocks with respect to weathering.

Porosity of intact rock

As weathering progresses, the general tendency is for the moisture content and the porosity to increase, while the density is reduced. The changes of the density and of the moisture content are a direct result of the increase of the porosity, caused by solution and the fracturing which accompanies the weathering. Porosity is an important index property which is frequently used for the classification of weathering grades (Table 1). Porosity of a rock can be determined through microscope examination, permeability test, sonic velocity and other geophysical measurements.

Fracture spacing index and rock quality designation (RQD)

The spacing of the fractures normally decreases with increased weathering. The fracture spacing index can therefore be an indication of the weathering for a rock mass. The Rock Quality Designation (RQD) is widely used to classify the rock masses. It is a function of the fracture spacing and of the conditions of the fractures. RQD is therefore a measure of the degree of weathering and is one of the property indexes in Table 1. Very little data are available, but it is suggested that RQD decreases as the weathering grade increases from Grade III. For rock less weathered than Grade III, RQD is mainly dependent on the original fracture spacing, and independent of the weathering. It is not a sensitive indicator of the weathering in Grades I and II.

Relative rock material and mass permeabilities

The changes of the porosity which occur as weathering proceeds affect the permeability of the rock material and of the rock mass. However, particularly in the more advanced stages of weathering, some factors, such as the development and dispersal of clay minerals, and the deposition of secondary cements, may reduce the permeability. Such changes have been observed in the Bukit Timah granite. The rock mass permeability is the highest in the highly fractured and weathered zones of Grades IV and V. It is rediced in the residual soil (Grade VI).

Changes of the permeability from 10^{-6} to 10^{-8} cm/s for the slightly weathered (Grade II) granite, to 10^{-4} cm/s in the completely weathered (Grade V) rock material have been recorded (Beavis, 1985).

Micropectrographic and microfracture indexes of rock material

Indexes such as rock/soil ratio, point load strength index, fracture spacing and RQD are determined in the field. It has been proposed recently that micro-indexes, which are determined in the laboratory on the rock material examined microscopically, are also of considerable value. These indexes can be used to supplement and to refine the field classification. The two indexes are the micropetrographic index and the microfracture index.

Table 3 : Micro-indexes of weathering for a granitic rock (after Irfan and Deraman, 1978b).

Weathering class	Grade	Micropetrographic	Microfracture
Fresh rock	I	> 12	< 0.5
Slightly weathered	II	6-12	0.5-2
Moderately weathered	III	4-6	2-5
Highly weathered	IV	2-4	5-10
Completely weathered	V	< 2	> 10

The micropetrographic index is defined as the ratio of the percentage sound constituents to the percentage of unsound constituent. The 'sound constituent' are the primary minerals, while 'unsound constituents' are secondary minerals, produced by the weathering, such as sericite, clay and iron oxides, together with microcracks and microvoids resulting from alterations (Baynes and Dearman, 1978a, 1978b, 1978c; Irfan and Dearman, 1978b; Zhao and Brown, 1992).

The microfracture index is the number of microcracks in a 1 cm traverse of a thin section including stained grain boundaries, open grain boundaries, stained and infilled microcracks in quartz and feldspars, pores and transgranular microcracks in the rock material (Baynes and Deraman, 1978a, 1978b, 1978c; Irfan and Dearman, 1978b).

These indexes can be determined readily for coarse textured rock such as granites. The application to fine grained rocks is difficult (Irfan and Dearman, 1978b; Beavis, 1985). The range of values of these indexes is shown in Table 3 for a weathered granite.

Proposed classification for the Bukit Timah granite

A granitic rock weathering classification system is proposed as an attempt to introduce an engineering weathering description and classification for the granitic rocks in Singapore. It combines the uses of geological identification, engineering recognition and laboratory testing. The classification system presented in Table 4 is proposed for both rock material and rock mass of the Bukit Timah granite. Its use for other rocks such as sedimentary rocks of the Jurong Formation should be carefully examined.

The proposed rock material weathering description and classification proposed is based on geological informations obtained by visual inspection of the chemical decomposition and of the physical disintegration of the rock at the site, and on the mechanical, hydraulic and physical information derived from field and laboratory tests, supplemented by the microscopic observations. The rock mass weathering description and classification proposed for the Bukit Timah granite is based on the identification of the various grades of weathering and on the volumetric proportions of these materials with respect to discontinuities.

Table 4 : Proposed weathering scheme for the Bukit Timah granite material and mass.

Weathering class	Grade	Geological description of rock material from core Description of rock block	Strength indexes σ_c	I_{s50}	S	P
Fresh granite (F)	I	All mineral constituents are sound. Feldspars cannot be cratched with knife. Material is fresh or slightly weatered. Many blows of geological hammer is required to fracture the rock. Surface of rock block is fresh or slightly weathered	> 180	> 8	> 60	–
Slightly weathered (SW)	II	Plagioclases are occasionally slightly decomposed. Biotites are slightly decomposed, begin to stain the surrounding. Slightly weaker than the fresh rock Rock block inner material is slightly weathered; block surface material is slightly or moderately weathered.	110-180	5-8	40-60	–
Moderately weathered (MW)	III	Most of plagioclases and some potash feldspars are moderately decomposed. Biotites are moderately decomposed, staining the surrounding. Feldaprs can be cratched with a knife. Sample can be fractured by a single firm blow with a geological hammer. Core cannot broken by hand. Considerably weaker than the fresh rock. Rock block inner material is moderately weathered; surface material is moderately or highly weathered, occasionally completely weathered	50-110	2-5	20-40	–
Highly weathered (HW)	IV	All plagioclases are highly decomposed. Most potash feldspars are moderately decomposed. Biotites are highly decomposed staining most of the rock. Feldspars can be peeled by a knife with difficulty. Cores may be broken by hand with difficulty. Can be excavated with a spade with great difficulty. Significantly weaker than the fresh rock. Rock block inner material is highly weathered; surface material is highly or completely weathered, occasionally residual soil.	< 50	< 2	< 20	> 15
Completely weathered (CW)	V	All plagioclases and most of potash feldspars and biotites are completely weathered. Original texture present. Fledspars can be readily peeled by a knife. Can be excavated by hand with some effort. Cannot be indented by thumb. Very low strength compared with the fresh rock. Most of rock block material is completely weathered.	< 1	–	–	< 15
Residual soil (RS)	VI	Feldspars and biotites are completely decomposed (clayey). Original textures are absent. Sample can be indented by thumb with moderated effort. Can be easily excavated by hand. Very low strength compared with the fresh rock.	< 1	–	–	–

Note σ_c = uniaxial compressive strength, MPa ; I_{s50} = point load index, MPa. S = Schmidt rebound hardness index; P = hand penetrometer index.

Field observation on the weathering of the Bukit Timah granite

The Bukit Timah granite is mainly an acidic igneous rock formed in lower middle Triassic period (about 230 million years ago), and covers about one third of the area of Singapore Island (Fig. 4). The granite, in general, varies from granite through ademalite to granodiorite, and there is considerable hybridization of rocks within the formation and evidence of assimilation (PWD, 1976; Pitts, 1984). The rock is usually light grey and medium to coarse grained (2-5 mm). The pink variety of orthoclase is also present. The main minerals are quartz (30 %), feldspar (60-65 %), biotite and hornblende. Due to the humid tropic environment in Singapore, the weathering of the granite has been rather rapid, and is primarily by chemical decomposition.

Recently, a detailed site investigation has been conducted to study the granite for its potential use for underground construction (Zhou *et al.*, 1992; Lee *et al.*, 1993) (Fig. 4). Coupled with site investigations, studies on the weathering of the Bukit Timah granite have been carried out to assess the engineering properties of the weathered rock as well as the extent of the weathering (Zhao *et al.*, 1992).

Field observations at some granite quarries in Singapore indicate that the weathering of the Bukit Timah granite has been rapid and is primarily due to decomposition. The granite may be overlain by a thick layer of residual soil. The granite residual soil is mainly sandy clayey silt. In some locations, a layer of reddish brown sandy

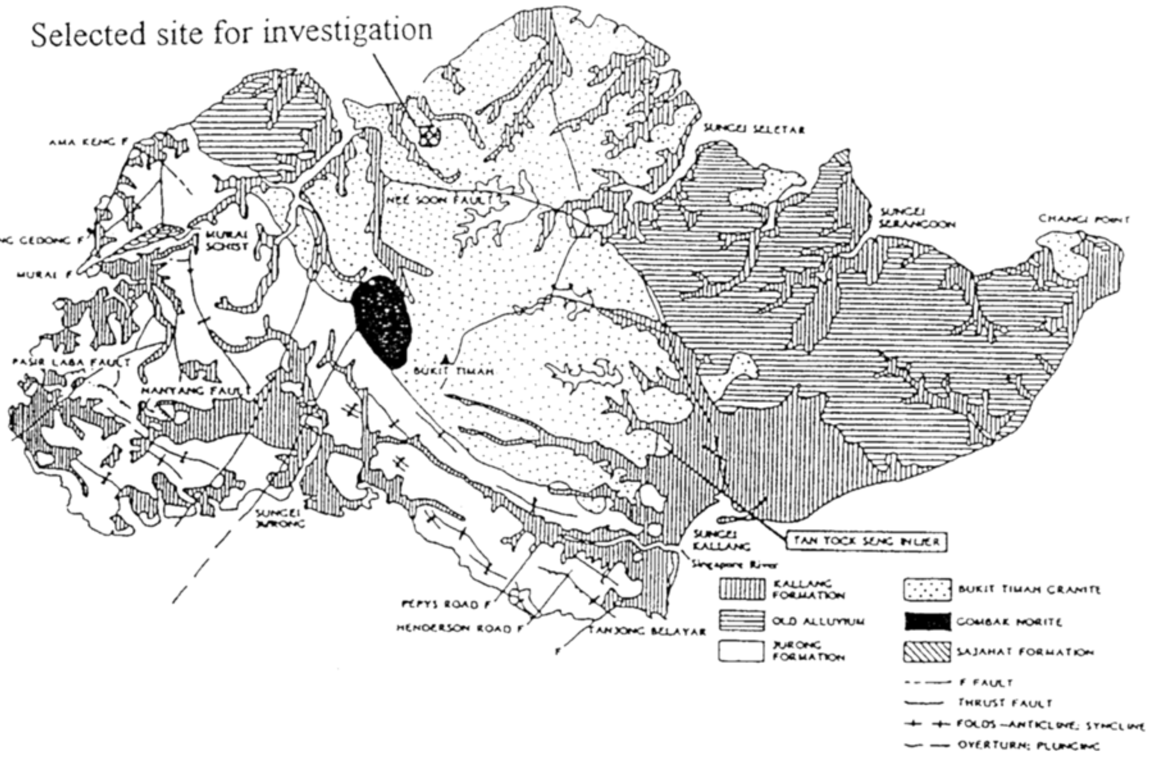


Fig. 4 : Generalized geology map of Singapore (after Pitts, 1984).

Fig. 5 : The Bukit Timah granite at Mandai Quarry. The vertical profile shows stratified layers with a sharp boundary between residual soil and slightly to moderately weathered rock.

silty clay with a thickness of a few meters can be found above the clayey silt as an indication the occurrence of secondary weathering. There is little variation in weathering grade in the residual soil and corestone are rare. However, the increase of the grain size with depth indicates that the weathering becomes less intense with depth. The residual soil also shows a steady but marked decrease in the clay content with depth. The residual soil of the Bukit Timah granite is generally stiff to hard, and has totally lost its rock texture and most of its strength. In many low lying areas, a sudden change from Grade VI to Grade III or possibly Grade II is common (Fig. 5). The residual soil is often stratified due to re-deposition of iron compounds as hard pans, zones of fines enrichment or fines depletion, and concentrated organic layers.

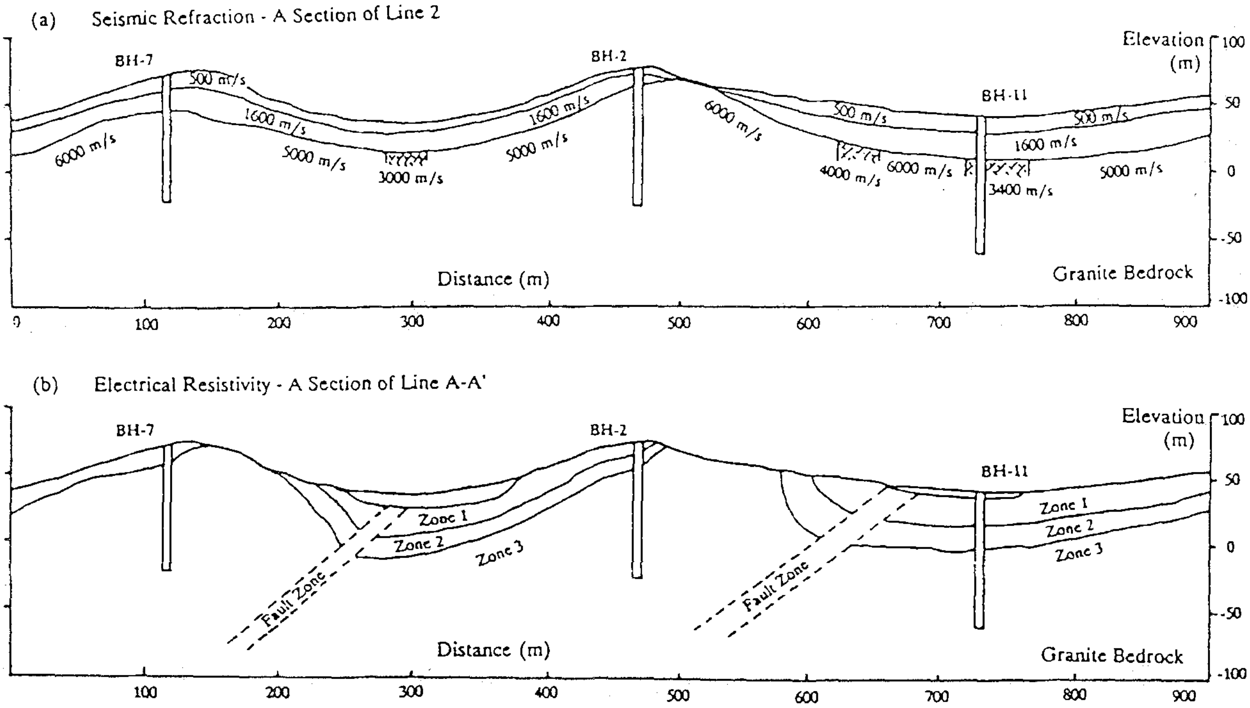


Fig. 6 : Typical weathering and bedrock quality profiles interpreted by (a) seismic refraction and (b) electrical resistivity methods along a selected line.

Weathering profiles interpreted by geophysical surveys

Geophysical surveys using refraction and electrical resistivity profiling methods have been carried out to determine the thickness of the residual soil and the quality of the bedrock. Both geophysical methods provide information of the depth of the overburden and of the bedrock quality. (Fig. 6 shows typical weathering profiles based on seismic refraction surveys and electrical resistivity profiling along a selected line.

Until recently, it has been commonly believed that the maximum depth of weathering in Singapore is 30 meters (Pitts, 1984; Poh *et al.*, 1987). However, weathering profiles interpreted from the seismic fraction and electrical resistivity surveys show that the depth of the residual soil ranges from a few meters to 70 meters. In most areas the range is 20-50 meters. Profiles of both methods indicate two distinct layers in the residual soil with different seismic velocity and electrical resistivity. The boundary of the two layers in the soil is likely the groundwater table. A seismic velocity of 1,600 to 2,000 m/s indicates that the soil is saturated. The secondary weathering occurs next to the ground surface down to a few meters depth. The weathering profile is of the skippingly stratified type rather than the correstone profile which is common elsewhere (Thomas, 1974; Stallard, 1985). The statified type of weathering profile of the Bukit Timah granite has also been observed and reported by Pitts (1984) and by Poh *et al.*, (1985).

Detailed field investigations and laboratory testing have also been carried out in order to characterize the weathered granite and the residual soil. The field investigation involved drilling, borehole testing and logging (including geophysical logging). Physical and mechanical tests on the residual soil and on the weathered rock samples were conducted in laboratory. Results from the field and the laboratory investigations are presented in Part B.

Conclusions

The process of weathering may be defined as that process of alteration of rocks caused by the direct influence of the hydrosphere and the atmosphere. The rate at which the various weathering processes take place is a function of environmental conditions, the properties of the rock mass and of the rock material. In a humid and hot climate, decomposition is far more effective than disintegration.

The most frequently used classification system which was developed by Fookes *et al.*, and later modified by Dearman, was designed for granitic rocks. Six grades of weathering from fresh rock (Grade I) to residual soil (Grade VI) have been proposed. Criteria used for the classification include rock material and rock mass description, rock/soil ratio, slakability, strength indexes, sonic velocity, porosity, fracture spacing index and rock quality designation, rock mass permeability, and micro-indexes (micropetrographic index and microfracture index).

A modified weathering classification system is proposed in the paper as an attempt to introduce an engineering weathering description and classification of the weathered granitic rocks in Singapore. It is based on geological identification, engineering recognition and laboratory testing. The proposed classification system can be used for both the rock material and the rock mass of the Bukit Timah granite.

Field and laboratory studies on the weathered Bukit Timah granite show that the rock has been weathered up to 70 meters deep. The main mechanism of the weathering is chemical decomposition. The humid tropic conditions in Singapore with high annual precipitation have caused secondary weathering of the resisual soils. The weathering profiles and field observations suggest that the weathering of the Bukit Timah granite is stratified and with a sharp boundary between the residual soil and the slightly to moderately weathered granite.

Detailed field investigations and laboratory testing have been carried out to characterize the weathered granite and the residual soil. Results from field and laboratory investigations are presented in Part B.

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