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Characterisation of the weathering profile developed over an amphibole schist bedrock in Peninsular Malaysia

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Abstract: Five stages of weathering of an amphibole schist bedrock material were distinguished on the basis of differences of colour, texture and the extent of alteration of original mineral grains. These stages of weathering are of a gradational nature except for the abrupt transition between unweathered bedrock material, and bedrock material weathered to the condition of an engineering soil. These stages of weathering are differently distributed within the weathering profile and determination of their distribution pattern allowed for the recognition of several morphological horizons. These morphological horizons are considered to represent different stages of weathering of the bedrock on the scale of the mass and can be assigned rock mass weathering grades.

INTRODUCTION

Published papers discussing the characterisation of weathering profiles for engineering geological purposes have so far been mainly concerned with profiles developed over granitic bedrock and there is little published data on the characterisation of profiles developed over other bedrock types. This is particularly true of the weathering profiles developed over metamorphic bedrock in humid tropical areas whose characterisation has so far mainly involved the differentiation of morphological horizons and zones (Vargas, 1953, 1971; Sowers, 1963; Deere and Patton, 1971). This approach to characterisation of weathering profiles has, however, received some criticism (Dearman, 1974) and is somewhat inconsistent with more recent approaches that emphasize recognition of the distinction between the weathering of rock material and the weathering of rock mass (Dearman, 1974, 1976; Baynes *et al.*, 1978; Irfan and Dearman, 1978). Recognition of this distinction in the case of most weathering profiles developed over metamorphic bedrock is difficult in view of the generally heterogenous and anisotropic character of metamorphic rocks. In some cases, however, where the weathering profile is developed over a relatively homogenous metamorphic bedrock, it is then possible to recognize the distinction between the weathering of rock material and the weathering of rock mass.

In Peninsular Malaysia, deep weathering profiles are found over a wide variety of bedrock types and have developed largely as a result of prolonged weathering throughout the Cainozoic (Raj, 1982). Several of these profiles are developed over metamorphic bedrock and are well exposed in recent deep cuts excavated during the construction of highways. In this paper is described the characterisation of one of these deep profiles developed over a relatively homogenous metamorphic bedrock (i.e. an amphibole schist consisting mainly of tremolite-actinolite, and lesser zoisite-clinozoisite, layers); characterisation being based on recognition and definition of different stages of weathering of the bedrock, both as rock material, and as rock mass.

GEOLOGICAL SETTING AND BEDROCK DESCRIPTION

The investigated weathering profile is exposed at a recent slope cut along the Kuala Lumpur-Karak Highway (Fig. 1) and is developed over a strongly jointed metamorphic bedrock that has been referred to as an amphibole schist (Ghani, 1977). The bedrock outcrops as a lenticular shaped body and forms one of many such bodies occurring within a sequence of tightly folded and strongly deformed quartz-mica, and graphitic-quartz-mica, schist outcropping on the eastern flanks of the Main Range Granite near the town of Bentong (Fig. 1). Various varieties of amphibole schist can be observed in these isolated bodies and include chlorite-epidote-actinolite schist, epidote-chlorite-actinolite-quartz schist and quartz-chlorite-actinolite schist (Alexander, 1968). Some of these varieties are distinctly banded, being composed of light green, and dark green, coloured layers, though others are massive and show no megascopic layering. The surrounding quartz-mica, and graphitic-quartz-

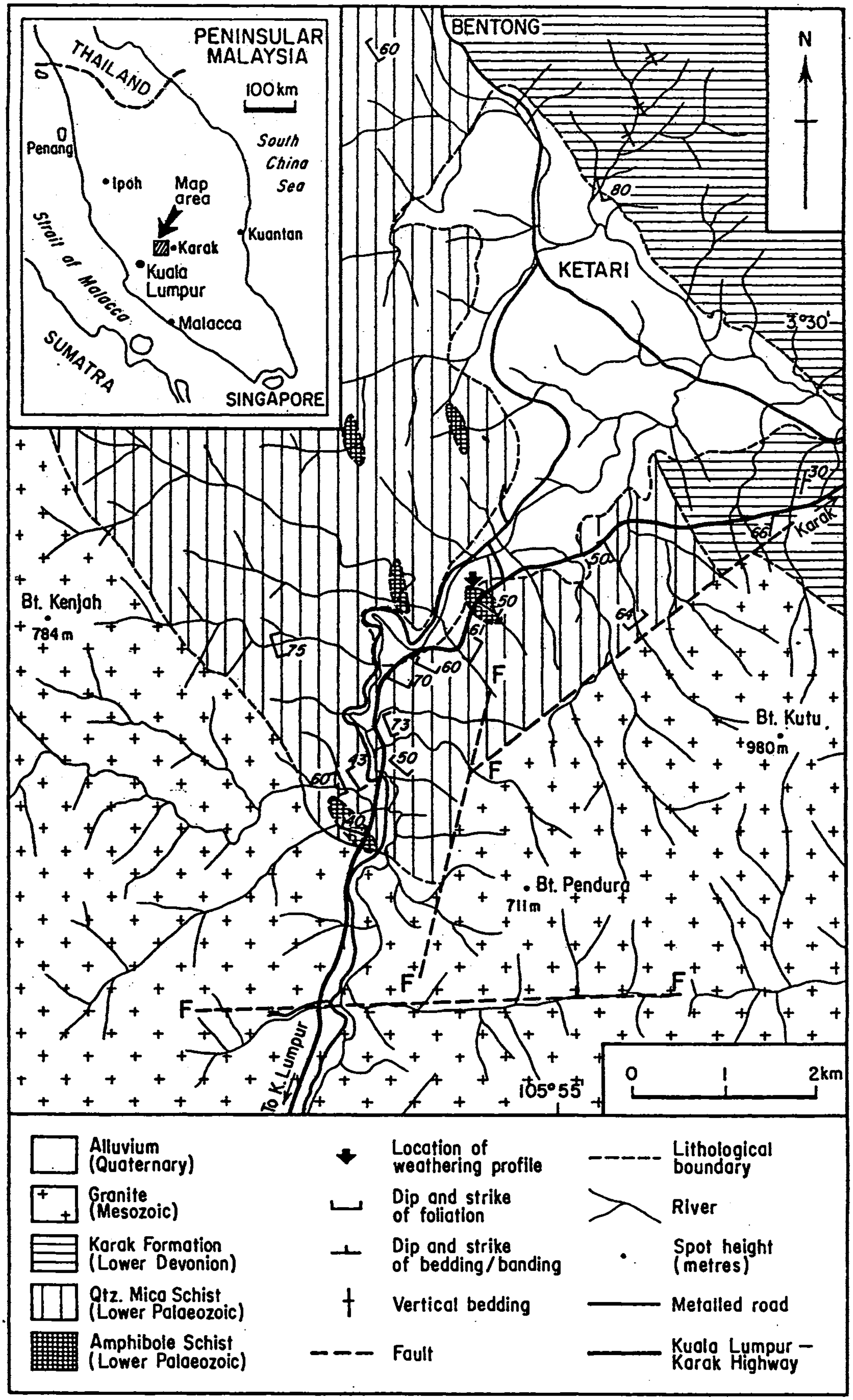

Figure 1. Geological sketch map of the Bentong area, Pahang (After Krishnan, 1974; Jaafar, 1976; Ghani, 1977).

mica, schists have resulted from the low grade regional metamorphism of interbedded sequences of sandstones and shales (Alexander, 1968) and outcrop, together with the amphibole schist bodies, in an undulating to hilly, fluvially dissected terrain. The origin of the amphibole schists is, however, uncertain though they are generally considered to result from the regional metamorphism of basic igneous rocks that occurred as flows or intrusive sheets within the pre-metamorphic sequences (Alexander, 1968; Jaafar, 1976).

At the site of the investigated weathering profile, the underlying, exposed bedrock mass shows a distinct, though often streaky, compositional banding of thin, dark green, and lesser light green, coloured layers which are up to about 5 cm in individual thickness. The compositional banding, which strikes 110° and dips 50° towards NE, is furthermore, usually accentuated by a parallel alignment of thin, elongate and streaky quartz lenses. Numerous thin quartz veins of variable orientations also cut through the exposed bedrock. In thin-section, the darker coloured layers are seen to consist predominantly of fine grained, aligned, fibrous aggregates of tremolite-actinolite with some zoisite-clinozoisite, chlorite, sphene and opaque minerals, while the light coloured layers are seen to consist mainly of fine grained, granular zoisite-clinozoisite with some tremolite-actinolite, chlorite, sphene and opaque minerals. Small lensoid bodies of xenoblastic quartz are also sometimes seen within the darker coloured layers. In view of this mineralogical composition, the bedrock can be best classified as being a tremolite-actinolite-zoisite-clinozoisite schist. The exposed bedrock is furthermore, jointed with two main sets, of about 0.5 m spacing, that are developed perpendicular to each other and to the banding. Within the lower part of the weathering profile, a few corestones and coreboulders (of up to 0.5 m maximum length) of tetrahedral shapes are also found.

STAGES OF WEATHERING OF THE BEDROCK MATERIAL

Weathering of the bedrock, considered on the scale of the hand specimen (i.e. as rock material) follows a limited number of stages, each of which is characterised by not only colour and texture (Table 1), but also by several physical properties (Tables 2 and 3) that include in some stages descriptive soil properties. These stages of weathering are of a sequential character in that each stage is followed successively by the next (increasing) stage of weathering. These stages of weathering are also of a gradational character, particularly between Stages 2 and 5, with each stage grading progressively into the next (increasing) stage of weathering. There is, however, a very distinct boundary between material (on the scale of the hand specimen) that can be termed 'rock' or 'soil' in an engineering sense (Terzaghi and Peck, 1948). The unweathered bedrock material (Stage 0) and the bedrock material showing Stage 1 weathering can be distinctly termed 'rock' material, though the bedrock material weathered through Stages 3 to 5 is distinctly 'soil' material. Stage 2 weathered bedrock material cannot, however, be distinctly termed 'rock' or 'soil' in an engineering sense and is best regarded as being material that is transitional between 'rock' and 'soil' material. This Stage 2 weathered bedrock material is furthermore, only of a narrow thickness (of up to about 5 cm) and is found as an irregular, thin concentric layer around the corestones and coreboulders (Fig. 2), or as a thin, irregular veneer over the underlying, exposed bedrock mass. Around the corestones and coreboulders, the Stage 2 weathered bedrock material is thickest parallel to the banding and is preferentially developed along the lighter coloured, zoisite-clinozoisite layers (Fig. 3). In view of the narrow thickness of the Stage 2 weathered bedrock material, it can be said that there exists an abrupt boundary between the unweathered bedrock material and the bedrock material weathered to the condition of an engineering soil. This feature is therefore very different from that shown by the weathering of granitic bedrock material in which the similar transition occurs over a wider and more gradational zone (Raj, 1986).

In the bedrock material weathered to the condition of an engineering soil (i.e. Stages 3 to 5) furthermore, the original texture of the bedrock material is indistinctly to distinctly preserved indicating *in situ* alteration. Stages 3 and 4 weathered bedrock material also show a gradational transition as seen from the results of descriptive and index soil properties (Table 3) of samples collected at different depths within the weathering profile (Fig. 4). Stages 5 weathered bedrock material has, however, been modified in part by the operation of pedological processes and forms the parent material for the development of the overlying pedological soil horizons.

From Table 1, it can be seen that zoisite and clinozoisite are the earliest minerals to be affected by weathering, being altered to gibbsite in the Stage 2 weathered bedrock material. Tremolite and actinolite are also affected by weathering at this Stage (being finer grained and showing weaker birefringence), though still relatively less altered than the zoisite and clinozoisite. Further alteration of these minerals, in the later stages of weathering of the bedrock material, results mainly in decreasing

Table 1. Stages of weathering of the amphibole schist bedrock material.

Stage of Weathering	Hand specimen description and comments
0	Rock material shows thin, dark and light green coloured bands with mineral grains that appear fresh and unaltered. Mineral grains show vitreous to sub-vitreous lustres. In thin-section, darker coloured bands are seen to consist predominantly of aligned, fibrous aggregates of tremolite-actinolite with some zoisite-clinozoisite, chlorite, sphene and opaque minerals, while lighter coloured bands are seen to consist mainly of fine, granular, zoisite-clinozoisite with some tremolite-actinolite, chlorite, sphene and opaque minerals. Apart from opaque minerals, all mineral grains appear fresh and unaltered (Unweathered rock material).
1	Black to dark brown coloured surficial stains seen along fracture planes delimiting blocks of banded light and dark green coloured, rock material. Stains do not penetrate into the rock material which shows similar features as those of Stage 0 unweathered rock material. In thin-section, rock material shows similar features as those of Stage 0 unweathered rock material.
2	Light to dark brown coloured (stained) 'rock' material which does not appear to contain any fresh and unaltered mineral grains. 'Rock' material distinctly preserves the texture of the original rock material and, although easily crushed by hand, does not disaggregate when dry samples are soaked and agitated in water. 'Rock' material represents transitional stage in weathered bedrock material that can be termed rock or soil material in an engineering sense. In thin-section, brown stains of iron oxides and hydroxides (including goethite and limonite) are seen to pervade the 'rock' material which consists of partly altered tremolite-actinolite grains (showing decreased birefringence) and completely altered zoisite-clinozoisite grains (altered to gibbsite). Quartz grains appear fresh and unaltered as do most chlorite and sphene grains.
3	Yellowish to light brown coloured, stiff, silty soil material which distinctly preserves the texture of the original rock material and which readily disaggregates when dry samples are soaked and agitated in water. Coarse fraction of the material consists of fresh quartz grains, sericite flakes, opaque minerals and many brown-coloured, silt sized flakes (altered tremolite-actinolite grains), while the clay fraction[1] consists of kaolinite and gibbsite.
4	Pinkish to yellowish coloured, stiff, silty soil material which distinctly preserves the texture of the original rock material and which readily disaggregates when dry samples are soaked and agitated in water. Coarse fraction of the material consists of fresh quartz grains, sericite flakes, opaque minerals and a few brown coloured, silt sized flakes (altered tremolite-actinolite grains), while the clay fraction[1] consists of kaolinite, gibbsite, goethite and halloysite.
5	Red coloured, stiff, clayey soil material which indistinctly preserves the texture of the original rock material and which disaggregates when dry samples are soaked and agitated in water. Coarse fraction of the material consists of fresh quartz grains and sericite flakes, while the clay fraction consists of kaolinite, gibbsite, goethite and halloysite. Soil material forms the parent material for the overlying soil horizons and has a high clay content that may be due in part to illuviation of clay from the overlying soil horizons.

Note: [1] identified from X-ray diffractograms of the clay sized fractions.

Table 2. Some physical properties of samples of unweathered, and Stages 1 and 2 weathered, amphibole schist bedrock material.

Sample Number	Mineral grain specific gravity[1]	Dry bulk density[1] (g/cm^3)	Saturated bulk density[1] (g/cm^3)	Total porosity[1] (%)	State of weathering
B1	3.05	3.03	3.04	0.5	0
B2	3.03	3.01	3.02	0.6	0
B3	3.02	2.99	3.10	0.6	1
B4	2.66	1.98	2.25	25.4	2
B5	2.92	2.09	2.37	28.5	2
B6	2.65	1.89	2.17	28.5	2
B7	2.60	1.53	1.94	41.1	2
B8	2.63	1.54	1.96	41.3	2

Note: [1]determined following Belikov *et al.* (1967).

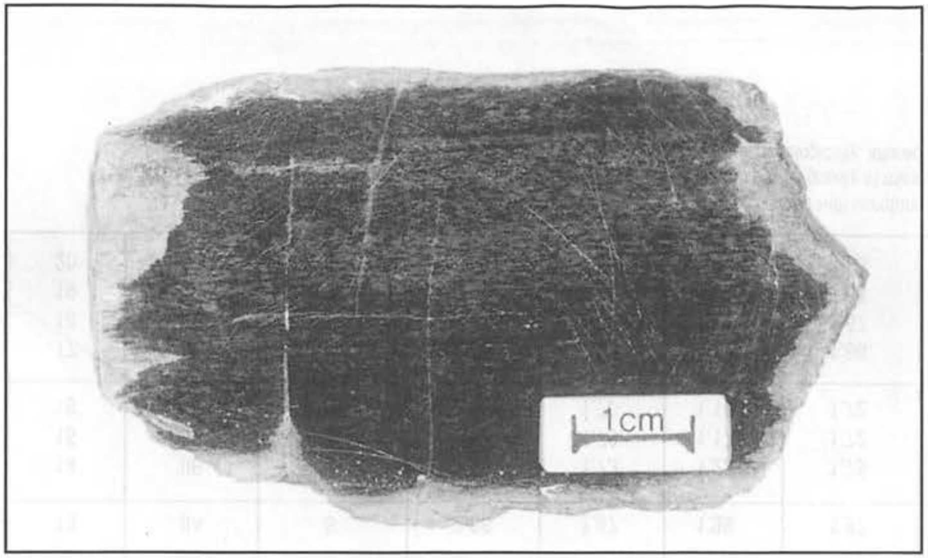

Figure 2. Corestone of unweathered amphibole schist bedrock material (dark toned) showing concentric rim, and preferential development, of Stage 2 weathered bedrock material (light toned) (Note: Banding is parallel to base line of scale).

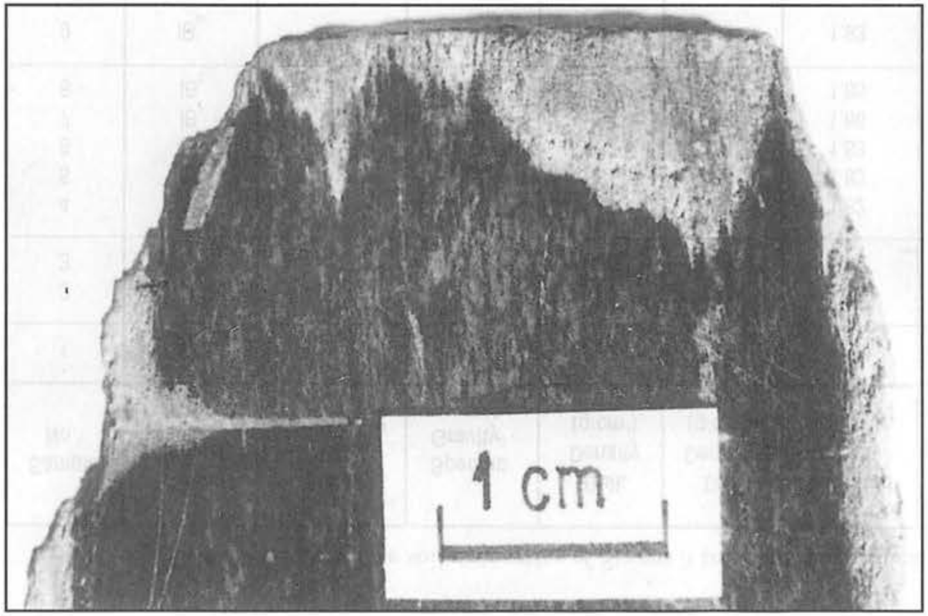

Figure 3. Close-up unweathered amphibole schist corestone showing preferential development of Stage 2 weathered bedrock material along zoisite-clinozoisite layers and along quartz vein.

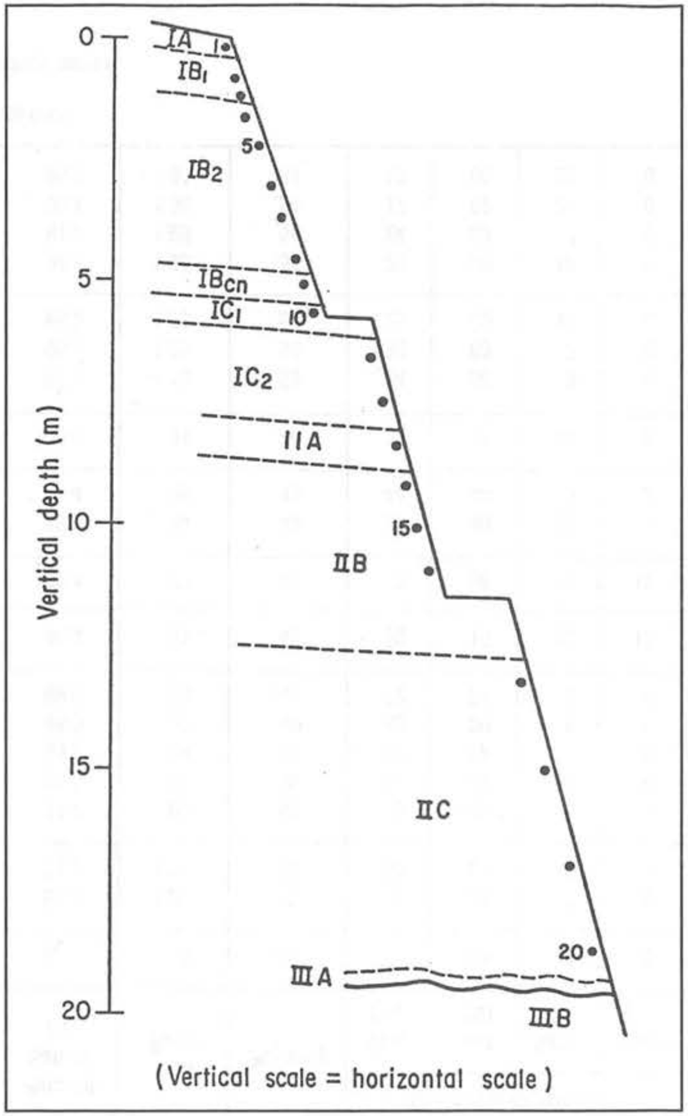

Figure 4. Sample location, and lateral extensions morphological horizons, within the weathering profile over the amphibole schist bedrock (5. sample number and location).

Table 3. Descriptive soil properties of Stages 3 to 5, and pedologically altered, weathered amphibole schist bedrock material.

Sample No.[1]	Morpho-logical Horizon	Stage of Weathering	Specific Gravity[2]	Bulk Density (g/cm^3)	Dry Density (g/cm^3)	Saturated Density (g/cm^3)	Moisture Content (%)	Percent. Saturn. (%)	Void Ratio	Porosity	Grain size distribution			
											Clay (%)	Silt (%)	Sand (%)	Gravel (%)
1	IA	a[3]	2.65	1.67	1.23	1.76	36.0	82.1	1.16	.54	70	22	8	0
2	IB_1	a	2.65	1.67	1.20	1.75	38.9	85.3	1.21	.55	70	23	7	0
3	IB_1	a	2.65	1.60	1.20	1.75	38.3	73.2	1.21	.55	69	23	8	0
4	IB_2	a	2.64	1.80	1.32	1.82	35.6	94.7	.99	.50	73	19	8	0
5	IB_2	a	2.65	1.81	1.34	1.83	35.6	96.0	.98	.50	67	24	9	0
6	IB_2	a	2.65	1.82	1.34	1.83	36.4	98.2	.98	.50	69	24	7	0
7	IB_2	a	2.65	1.84	1.39	1.86	32.6	95.0	.91	.48	63	29	8	0
8	IB_2	a	2.65	1.84	1.36	1.85	35.5	99.0	.95	.49	72	21	7	0
9	IB_{cn}	a	2.69	1.91	1.48	1.93	28.5	94.4	.81	.45	50	15	22	13
10	IC_1	a	2.66	1.88	1.53	1.95	22.9	82.1	.74	.43	28	26	34	12
11	IC_2	5	2.65	1.79	1.37	1.85	30.5	86.5	.94	.48	37	40	19	4
12	IC_2	5	2.60	1.80	1.33	1.82	36.0	97.4	.96	.49	44	44	9	3
13	IIA	5	2.66	1.87	1.39	1.87	34.1	100.0	.91	.48	30	41	24	5
14	IIB	4	2.59	1.73	1.22	1.75	42.1	97.2	1.12	.53	34	58	8	0
15	IIB	4	2.59	1.70	1.17	1.72	44.8	95.8	1.21	.55	30	63	7	0
16	IIB	4	2.55	1.70	1.19	1.72	43.5	96.3	1.15	.54	25	62	13	0
17	IIC	3	2.53	1.65	1.12	1.68	46.7	94.5	1.25	.56	21	69	10	0
18	IIC	3	2.54	1.63	1.11	1.67	46.6	91.7	1.29	.56	24	69	7	0
19	IIC	3	2.51	1.60	1.09	1.66	47.8	92.1	1.30	.56	17	62	21	0
20	IIC	3	2.51	1.65	1.09	1.66	51.5	99.2	1.31	.57	19	60	21	0

Note: [1] samples collected with constant volume sampling rings.
[2] refers to specific gravity of mineral grains.
[3] a denotes pedologically, altered, weathered bedrock material.

particle sizes and increasing contents of clay minerals (Table 3). From Table 2, it can also be seen that initial effects of weathering on the bedrock material are reflected by an increase in porosity and a decrease in unit weights (density) as well as by a change in the specific gravity of the solid mineral constituents. In Table 3, however, it can be seen that increasing effects of weathering on the bedrock material weathered to the condition of an engineering soil (Stages 3 to 5) are marked by an increase in unit weights (density) and a decrease of porosity. This somewhat surprising feature is considered to result from increasing amounts of clay sized particles in the later stages of weathering as shown by the decreasing silt, and increasing clay, contents of the grain size analyses (Table 3).

STAGES OF WEATHERING OF THE BEDROCK MASS

The distribution pattern of the different stages of weathering of bedrock material within the weathering profile is very distinctive (Fig. 5 and Table 4) and allows for the recognition of a number of 'morphological' horizons; each of which is characterised by the presence of variable amounts of the different stages of weathering of bedrock material. In view of the fact that unweathered bedrock material, and early stages of weathering of bedrock material, predominate in the lower part of the weathering profile, and later stages in the upper part, it can be considered that the weathering profile reflects weathering of the bedrock on the scale of the mass. The 'morphological' horizons can thus be considered to represent different stages of weathering of the bedrock on the scale of the mass. It should be noted, however, that in contrast to weathering profiles developed over granitic bedrock (in which the percentage of 'rock' material decreases up the profile), it is more difficult to define different stages of weathering of the bedrock on the scale of the mass due largely to the abrupt boundary between unweathered bedrock material and bedrock material weathered to the condition of an engineering soil. This feature is furthermore, complicated by the structural influence on weathering of bedrock material within the weathering profile, as shown by the lateral variation and presence of different stages of weathering of bedrock material at approximately similar levels within the profile (Fig. 5).

In order to achieve uniformity with more recent approaches to characterisation of weathering profiles for engineering geological purposes, rock mass weathering grades can be assigned to the different 'morphological' horizons recognized. In view of the abrupt boundary between unweathered bedrock material and bedrock material weathered to the condition of soil, and the gradational boundary between the different stages of weathering, however, only three rock mass weathering grades can be properly assigned to the weathering profile. Definition of these three rock mass weathering grades (Table 4) follows criteria used in the definition of rock mass weathering grades in weathering profiles over granitic bedrock (Dearman *et al.*, 1978; Irfan and Dearman, 1978; Raj, 1986). It should be noted that there is a particularly thick pedological B horizon in the exposed weathering profile; a feature which is considered to result from the accumulation of surface wash material, rather than from the operation of pedological processes.

Within the exposed weathering profile, structural features of the original bedrock mass are seen preserved as indistinct to distinct relict structures at different levels (Fig. 5) and indicate that weathering of the bedrock (on the scale of the mass) has occurred *in situ*. The distribution pattern of the different stages of weathering of bedrock material (within the weathering profile) in relation to the relict structures (Fig. 5) furthermore, shows that weathering of the bedrock material has been controlled by the structural planes present in the original bedrock mass. This is particularly well illustrated by the linear extension of stages of weathering of bedrock material parallel to the metamorphic banding. Arising from these features, it can thus be said that the presently exposed weathering profile represents the end product of the weathering of an amphibole schist bedrock mass, where weathering of the bedrock mass has itself resulted from the structural plane controlled weathering of bedrock material.

CONCLUSION

Recognition and definition of the different stages of weathering of the amphibole schist bedrock material and determination of their distribution pattern within the weathering profile has allowed for characterisation of the profile. Characterisation of the weathering profile has thus involved recognition and definition of different stages of weathering of the bedrock, both on the scale of the hand specimen (i.e. as rock material) and on the scale of the mass (i.e. as rock mass).

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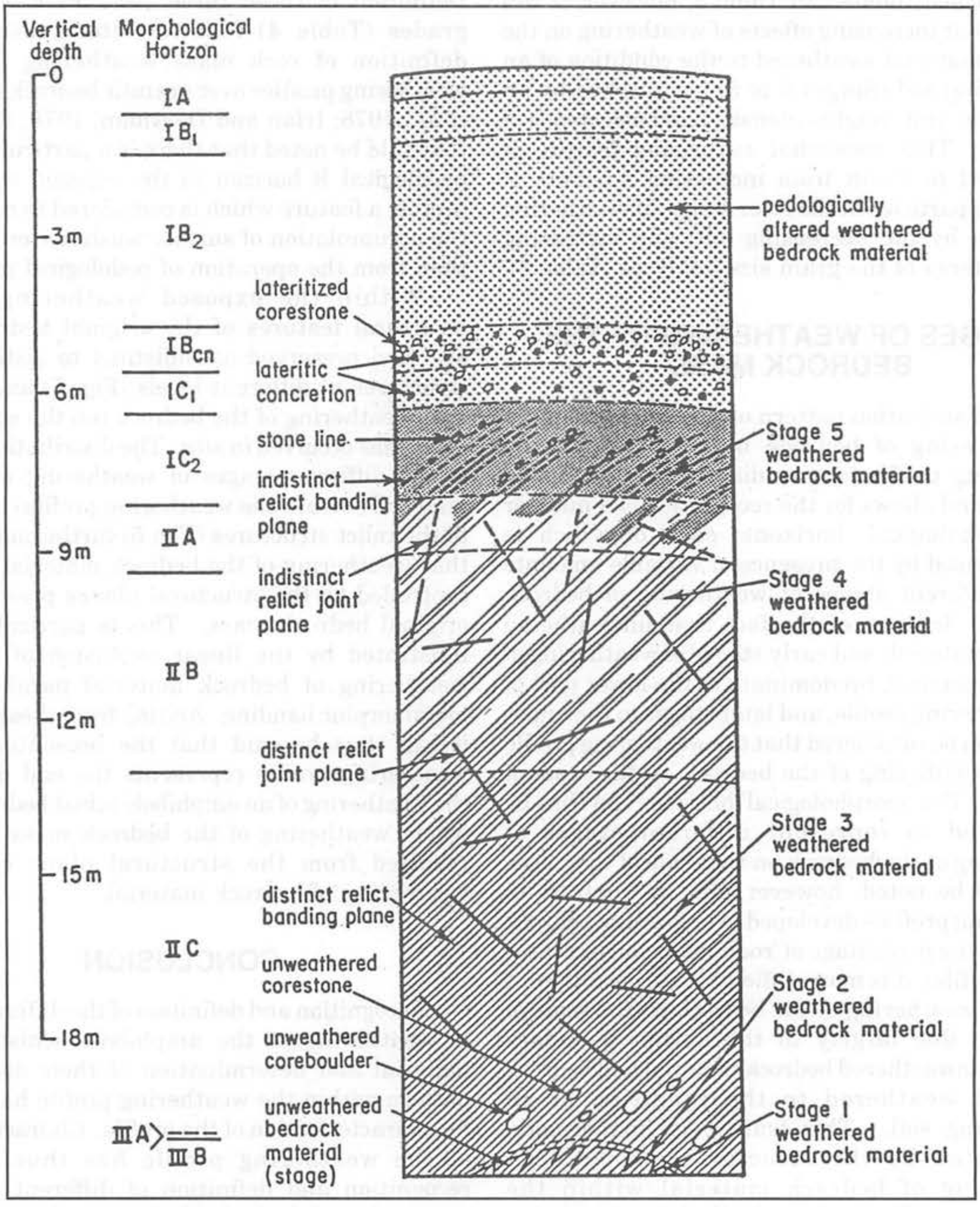

Figure 5. Schematic sketch showing the distribution of different stages of weathering of bedrock material within, and morphological features of, the weathering profile over the amphibole schist bedrock (Note: Stages of weathering are defined in Table 1.).

Table 4. Stages of weathering of amphibole schist bedrock material present in different 'morphological' horizons of the weathering profile.

Morphological Horizon	Depth[1]	Brief Field Description of Morphological Horizon (Including stages of weathering of bedrock material present)	Rock Mass Weathering Grade[2]
IA	0 – 0.48 m	Brown coloured friable clay with many roots and burrows. (Pedologically altered weathered bedrock material)	3
IB_1	0.48 – 1.44 m	Yellowish red coloured firm clay with some roots. (Pedologically altered weathered bedrock material)	
IB_2	1.44 – 5.22 m	Yellowish red coloured firm clay with no roots. (Pedologically altered weathered bedrock material)	
IB_{cn}	5.22 – 5.82 m	Red coloured firm clay with abundant gravel sized lateritic concretions, lateritized corestones and vein quartz clasts. (Pedologically altered weathered bedrock material)	
IC_1.	5.82 – 6.60 m	Red coloured stiff sandy clay with some platy lateritized corestones. (Pedologically altered weathered bedrock material)	
IC_2	6.60 – 8.52 m	Red coloured stiff clay with horizontal to dipping stone lines of gravel sized lateritic concretions, vein quartz clasts and lateritized corestones. (Dominantly Stage 5 weathered bedrock material)	
IIA	8.52 – 9.42 m	Bands of stiff, silty material of reddish, yellowish and pinkish colours of completely weathered bedrock material with distinct relict textures and banding planes and indistinct relict joint planes. (Dominantly Stage 4 weathered bedrock material with thin wedges and bands of Stage 5 weathered bedrock material)	2
IIB	9.42 – 13.44 m	Bands of stiff, silty material of differently coloured completely weathered and less weathered bedrock with distinct relict textures, banding and joint planes. (Alternating bands of Stages 3 and 4 weathered bedrock material with Stage 4 material forming approximately 50% by area of the material of this horizon)	
IIC	13.44 – 20.16 m	Thick bands of yellowish coloured, less weathered bedrock alternate with thin bands of pinkish coloured, silty, completely weathered bedrock with distinct relict textures, banding and joint planes. A few blocky corestones and coreboulders are also found. (Dominantly Stage 3 weathered bedrock material with thin bands of Stage 4 weathered bedrock material. Stage 4 material forms about 20% by area of the material of this horizon)	
IIIA	20.16 – 20.64 m	Continuous unweathered bedrock outcrop with weathering effects along, and between, structural planes. (Continuous unweathered (Stage 0) bedrock material with thin strips and wedges of Stages 2 and 3 weathered bedrock material along structural planes. Stage 0 bedrock material forms more than 90% by area of the material of this horizon)	1
IIIB	> 20.64 m	Continuous unweathered bedrock outcrop with weathering effects along structural planes only. (Continuous unweathered (Stage 0) bedrock material with Stage 1 weathered bedrock material along structural planes only)	

Note: [1] Depth measured along slope face from top of the cut.
[2] Rock mass weathering grades 1, 2 & 3 correspond to rock mass weathering grades 2, 3 & 6, respectively of weathering profiles over granitic bedrock (Dearman *et al.*, 1978; Irfan and Dearman, 1978; Raj, 1986).

REFERENCES

ALEXANDER, J.B., 1968. *The geology and mineral resources of the neighbourhood of Bentong, Pahang and adjoining portions of Selangor and Negeri Sembilan.* Dist. Mem. 8, Geol. Survey West Malaysia, 250p.

BAYNES, F.J., DEARMAN, W.R. AND IRFAN, T.Y., 1978. Practical assessment of grade in a weathered granite. *Bull. Int. Ass. Eng. Geol.*, 8, 101–109.

BELIKOV, B.P., ZALESSKII, B.V., ROZANOV, Y.A., SANINA, E.A. AND TIMCHENKO, I.P., 1967. Methods of studying the physico-mechanical properties of rocks. Chpt. 1 *in* B.V. Zalesskii (Ed.), *Physical and mechanical properties of rocks*, Israel Program For Scientific Translations, Jerusalem, 1–58.

DEARMAN, W.R., 1974. Weathering classification in the characterisation of rock for engineering purposes in British practice. *Bull. Int. Ass. Eng. Geol.*, 9, 33–42.

DEARMAN, W.R., 1976. Weathering classification in the characterisation of rock — A revision. *Bull. Int. Ass. Eng. Geol.*, 13, 123–127.

DEERE, D.V. AND PATTON, F.D., 1971. Slope stability in residual soils. *Proc. 4th Panam. Conf. Soil Mech. Found. Eng., Puerto Rico*, 1, 87–170.

GHANI, A., 1977. *Geological and geotechnical investigations in the Bentong area, Pahang.* B.Sc. (Hons) Thesis (Unpubl.), Dept. Geol., Univ. Malaya, 66p.

IRFAN, T.Y. AND DEARMAN, W.R., 1978. Engineering classification and index properties of a weathered granite. *Bull. Int. Ass. Eng. Geol.*, 17, 79–90.

JAAFAR, A., 1976. *The Geology and mineral resources of the Karak and Temerloh areas, Pahang.* Dist. Mem. 15, Geol. Survey Malaysia. 138p.

KRISHNAN, D., 1974. *Geology of the Bentong area, Pahang.* B.Sc. (Hons) Thesis (Unpubl.), Dept. Geol., Univ. Malaya, 83p.

RAJ, J.K., 1982. A note on the age of the weathering profiles of Peninsular Malaysia. *Newsletter, Geol. Soc. Malaysia*, 8(4), 135–137.

RAJ, J.K., 1986. Characterisation of the weathering profile developed over a porphyritic biotite granite in Peninsular Malaysia. *Bull. Int. Ass. Eng. Geol.*, 32, 121–129.

SOWERS, G.F., 1963. Engineering properties of residual soils derived from igneous and metamorphic rocks. *Proc. 2nd Panam. Conf. Soil Mech. Found. Eng., Brazil*, 39–62.

TERZAGHI, K. AND PECK, R.B., 1948. *Soil mechanics in engineering practice.* John Wiley & sons Inc., New York, 566p.

VARGAS, M., 1953. Some engineering properties of residual clay soils occurring in southern Brazil. *Proc. 3rd Int. Conf. Soil Mech. Found. Eng., Switzerland*, 1, 47–50.

VARGAS, M., 1971. Effectiveness of cut-offs under three earth dams. *Proc. 4th Panam. Conf. Soil Mech. Found. Eng., Puerto Rico*, 2, 257–273.

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