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Characterizing a weathering profile over quartz-mica schists in undulating terrain in Peninsular Malaysia

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Abstract: The weathering profile can be differentiated into an upper, 4.8 m thick, pedological soil (zone I) and a lower, >16.2 m thick, saprock (zone II). Zone I comprises thin IA and IB soil horizons of firm, clayey sand with lateritic concretions, and a IC soil horizon of stiff, clayey silt with quartz clasts and lateritized core-stones. Zone II comprises steeply dipping to vertical, bands of pinkish to grey, stiff silt with distinct relict foliation (highly weathered schist) inter-fingering with bands of reddish yellow, firm clayey silt with indistinct foliation (completely weathered schist) towards its top, and bands of white to light grey, hard silt with distinct foliation (moderately weathered schist) towards its bottom. Lateral variations in abundance of differently weathered schist and preservation of fracture planes allow zone II to be separated into IIA, IIB and IIC sub-zones. The pedological soil (zone I) can be correlated with Class VI of standard rock mass weathering classifications, whilst the saprock sub-zones IIA, IIB and IIC are correlated with Classes V, IV and III, respectively. Silt fractions in the profile consist predominantly of sericite flakes, whilst the sand fractions are mostly of quartz grains and the clay fractions of mainly illite and kaolinite. Decreasing densities, unit weights and silt contents up the profile, but increasing porosities and clay contents, indicate increasing *in situ* alteration of the schist bedrock. Lowering of an unconfined groundwater table as a result of down-cutting by rivers in adjacent valleys is considered responsible for development of the weathering profile.

Keywords: Quartz-mica schists, weathering profile, schist weathering stages, weathering zones

INTRODUCTION

Several schemes have been proposed for the classification of rock mass weathering; one of the earliest by Moye (1955) who applied seven recognition criteria, including the staining of joints, decomposition of feldspars and absence of original texture, to distinguish six grades or degrees of weathering of granite in Australia. In Hong Kong, Ruxton & Berry (1957) differentiated four weathering zones within an idealized weathering profile over granite on the basis of the absence of original texture, staining of fractures and percentage occurrence of core-stones. Several other characterizations of weathering profiles over granitic bedrock, as those by Little (1969), Deere & Patton (1971), Lan *et al*. (2003) and Rahardjo *et al*. (2004) have also involved the differentiation of weathering zones based on essentially morphological criteria.

Some criticism, however, has been levelled at the use of weathering zones for geotechnical purposes, as their recognition is said to be based on criteria that is not quantitative nor related to mechanical properties or engineering behaviour of material (Dearman, 1974). Stages of weathering of granitic rock material were then defined and used to differentiate grades of weathering in weathering profiles; the grades, in reality, applied to weathering zones (Dearman, 1976; Irfan & Dearman, 1978). The assignment of weathering grades is somewhat problematic for different stages of weathering of rock material are present at similar levels, as in the concentrically developed stages of weathering around core-stones and core-boulders (Dearman, 1976). The assignment of rock mass weathering grades is thus considered to be an averaging process dependent upon mapping scale; the resultant grades being proportions of different materials (i.e. rock materials at different stages of weathering) (Baynes *et al*., 1978).

In a review of several classifications of weathering of rock mass, as those by the Geological Society (GSL, 1977), the International Association of Engineering Geology (IAEG, 1981) and the International Society for Rock Mechanics (ISRM, 1981), Martin & Hencher (1986) were critical of the way in which the term *grade* was used both as a type of weathering of rock, and to classify a zone of heterogeneous rock mass. Martin & Hencher (1986) also noted the lack of definition or guidance for the description of rock material grades; in

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particular, the inadequate definition of the terms *rock* and *soil*. Lee & de Freitas (1989) then proposed that the term weathering zone be used to distinguish the character of material *en-masse*, while the term weathering grade is used to describe material from which the mass is formed. From a study of weathered granite in Korea, Lee & de Freitas (1989) concluded that it is necessary to combine geological descriptions with mechanical evaluation to describe weathered materials; this necessity being especially important for identification of relict geological structures as joint and fault planes (Raj, 2009).

In the humid tropics, as Peninsular Malaysia, deep weathering profiles are found due to prolonged sub-aerial exposure throughout a larger part of the Cenozoic era (Raj, 2009). Standard classifications of rock mass weathering as those by the International Association of Engineering Geology (IAEG, 1981) and the International Society for Rock Mechanics (ISRM, 1981) thus require considerable modification when applied to weathering profiles over meta-sedimentary bedrock in the Peninsula due to their continuous weathering to form residual soils (Komoo & Mogana, 1988). The total absence of fresh meta-sedimentary bedrock at surface outcrops, and in boreholes, also makes it difficult to define the boundary between rock and soil and thus disallows use of *rock:soil* ratios for classification of weathering (Komoo & Mogana, 1988). In sub-tropical Queensland, it has also been pointed out that not all six classes of the standard weathering classification of rock mass of the International Society for Rock Mechanics (ISRM, 2007) were present at weathering profiles over the Bunya Phyllite (Marques & Williams, 2015). There was also an abrupt contact between soil and rock material with the layers of different classes of soil material being very thin, frequently less than 0.7 m (Marques & Williams, 2015).

In the course of a study on the characterization of weathering profiles in Peninsular Malaysia (Raj, 1983), was investigated a deep profile over quartz-mica schists in undulating terrain at Seremban in Negeri Sembilan State. In this article is discussed the characterization of the profile in terms of differentiating weathering zones, and in terms of differentiating rock mass weathering grades. Reasons for development of the weathering profile are also discussed.

GEOLOGICAL SETTING OF WEATHERING PROFILE

The weathering profile is located at the slope cut at Km 67.9 (southbound) of the Kuala Lumpur - Seremban Highway and was exposed during earthworks for its construction (Figure 1). The Highway here cuts through a low hill and trends in a general west to east direction

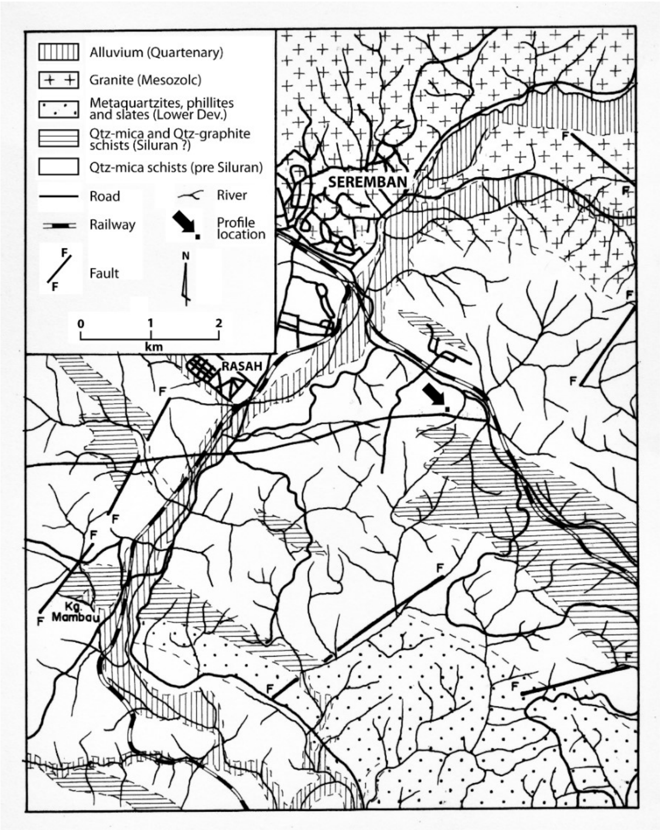

Figure 1: Geological sketch map of the Seremban area (after Khalid, 1972; Raj, 1993).

across an undulating terrain of low hills and ridges with narrow to broad, flat-bottomed valleys. The undulating terrain, located between some 50 and 100 m above mean-sea level, is developed over quartz-mica schists that have been correlated with the Lower Palaeozoic Dinding Schist of the Kuala Lumpur area (Khalid, 1972). The schists have an abundance of quartz lenses and pods and are highly deformed, whilst the flat-bottomed valleys are infilled with Quaternary alluvial sediments (Khalid, 1972; Raj, 1993).

Relatively less weathered bedrock at the base of the cut shows the weathering profile to be developed in light grey to buff, quartz-mica schists inter-layered with thin bands and lenses of dark grey, graphitic-quartz-mica schist (Photo 1). Indistinct to distinct preservation of the minerals and textures of the original schist in the exposed earth materials clearly indicates *in situ* development of the weathering profile. *In situ* development of the profile is further emphasized by the indistinct to distinct preservation of structural discontinuity planes inherent in the original bedrock material and mass, including foliation and fracture planes.

The relict foliation planes, though variable in detail, mainly strike north-south with very steep to vertical dips; an extremely fortuitous orientation for it allows variations in minerals and textures of individual lithologic units or sequences to be traced down-dip (i.e. down the profile). Lateral variations in relict minerals, textures and structures will therefore, reflect differences in lithologic units or sequences.

Photo 1: View of investigated weathering profile over quartz-mica schists.

In thin-sections, the relatively less weathered quartz-mica schist is seen to consist of thin layers (about 0.5 mm thick) of fine-grained quartz crystals in parallel alignment with thicker layers (up to 5 mm thick) of aligned sericite, muscovite and clay minerals. Relatively less weathered graphitic quartz-mica schist also shows a similar appearance, except for the presence of graphite in the thicker layers. In the thin-sections, secondary iron oxide and hydroxide stains and grains are often seen, whilst thin quartz veins and fissures are sometimes found perpendicular to the foliation.

Seepage was not seen at the cut, though perennial streams in adjacent valleys indicate the presence of an unconfined groundwater table at depth.

METHODOLOGY

The earth materials exposed at the cut were first described and mapped based on the Soil Survey Manual for Malayan Conditions (Leamy & Patton, 1966) and the Guidelines for Soil Description of the Food and Agriculture Organization (FAO, 2006). Pedological features described included colour, consistency and soil structure as well as the content of concretions, stains and organic matter. Geological features were also described and mapped, in particular the minerals, textures and structures of the original schist bedrock material and mass now indistinctly to distinctly preserved (as relict minerals, textures and structures) in the earth materials.

In order to better describe the earth materials present, constant volume samples were collected at various depths (Figure 2) to determine their physical and soil index properties. Brass tubes of 4 cm long and 7.6 cm internal diameter were used to collect the samples; the tubes having a constant wall thickness of 0.3 cm except

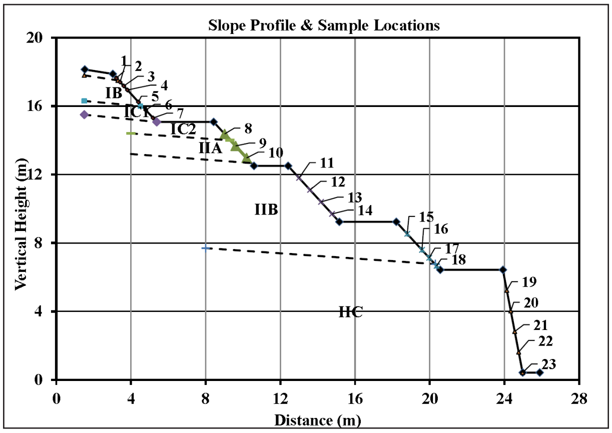

Figure 2: Slope profile and sample locations.

at one end where the lower half tapered to 0.15 cm thick to provide a cutting edge. Prior to sampling, the tubes were externally greased to facilitate entry into the soil while the surface materials were cleared to a depth of 0.3 m to minimize surface influences.

The sealed sampling tubes were taken to the laboratory where their moisture contents, unit weights and densities were determined before the specific gravity of the constituent mineral grains was measured using a pycnometer (ASTM, 1970). Porosities, void ratios and degrees of saturation of the samples were then calculated before the plastic and liquid limits of the fine fractions (<0.42 mm size) were determined (ASTM, 1970). Particle size distributions of the samples were next determined using the sieving, and sedimentation, methods for the coarse (>0.0625 mm diameter) and fine (<0.0625 mm diameter) grained fractions respectively (ASTM, 1970).

The main minerals present in the gravel, sand and silt sized fractions were then identified with the aid of a binocular microscope, whilst X-ray diffractograms of the clay fractions were prepared under normal, glycolated, and 500°C heated, conditions to determine the minerals present (Raj, 1993). It is to be noted that in view of a geological background, the size limits for particles follow the Wentworth (1922) Scale where gravel refers to particles with diameters between 2 and 64 mm, sand to particles with diameters between 0.0625 and 2 mm, silt to particles with diameters between 0.0039 and 0.0625 mm, and clay to particles less than 0.0039 mm in diameter.

RESULTS

Weathering zones and sub-zones

Vertical and lateral variations in the field mapped pedological and geological features allowed differentiation of the two upper zones of the pedo-weathering profile concept of Tandarich *et al*. (2002), i.e. the pedological soil, and saprock, zones. Several sub-zones can also be differentiated; the zones and sub-zones developed approximately parallel to the overlying ground surface (Table 1 and Figure 3).

The pedological soil (henceforth known as zone I) is some 4.8 m thick and comprises IA, IB and IC soil horizons (sub-zones); the IA and IB horizons constituting the solum, and the IC horizon, the saprolite. The IA and IB horizons are relatively thin and consist of yellowish red to red, firm clay and clayey sand with lateritic concretions, whilst horizon IC is 2.5 m thick and consists of reddish yellow, firm to stiff, clayey silt with vein quartz clasts

Table 1: Pedological and geological features of weathering zones and sub-zones.

Sub-zone	Thickness (m)	Pedological & Geological Features
IA	0.4	Yellowish red, firm clay with some roots and burrows.
IB	1.9	Red, firm clayey sand with abundant gravel sized lateritic concretions. Some lateritized core-stones and vein quartz clasts. Few roots.
IC1	1.3	Reddish yellow, stiff, clayey silt with some yellow mottles. Some gravel sized vein quartz clasts and lateritized core-stones.
IC2	1.2	Reddish yellow, firm clayey silt with some yellow mottles. Many gravel sized lateritized core-stones and vein quartz clasts. Distinct relict quartz veins and pods. Indistinct relict foliation. (Completely weathered schist).
IIA	2.2	Thick bands and wedges of reddish yellow, firm clayey silt with indistinct relict foliation (Completely weathered schist) alternating with thin bands of pinkish to grey, stiff silt with distinct relict foliation (Highly weather-ed schist). Distinct relict quartz veins and pods. Indistinct to distinct relict fracture planes. Some secondary iron stains and concretions along relict fracture planes. (Completely weathered schist >50% by area).
IIB	7.7	Thick bands of pinkish to grey, stiff silt (Highly weathered schist) alternating with thin bands of reddish yellow, firm clayey silt (Completely weathered schist). Towards bottom of sub-zone, some thin bands of white to light grey, hard silt (Moderately weathered schist). Distinct relict foliation and fracture planes as well as quartz veins and pods. Some iron concretions and stains along fracture planes. (Highly weathered schist >70% by area).
IIC	>6.3	Thick bands of white to light grey, hard silt (Moderately weathered schist) alternating with thin bands of pinkish to grey, stiff, silt (Highly weathered schist). Distinct relict foliation and fracture planes as well as quartz veins and pods. Rare secondary iron stains along fracture planes. (Moderately weathered schist >70% by area).

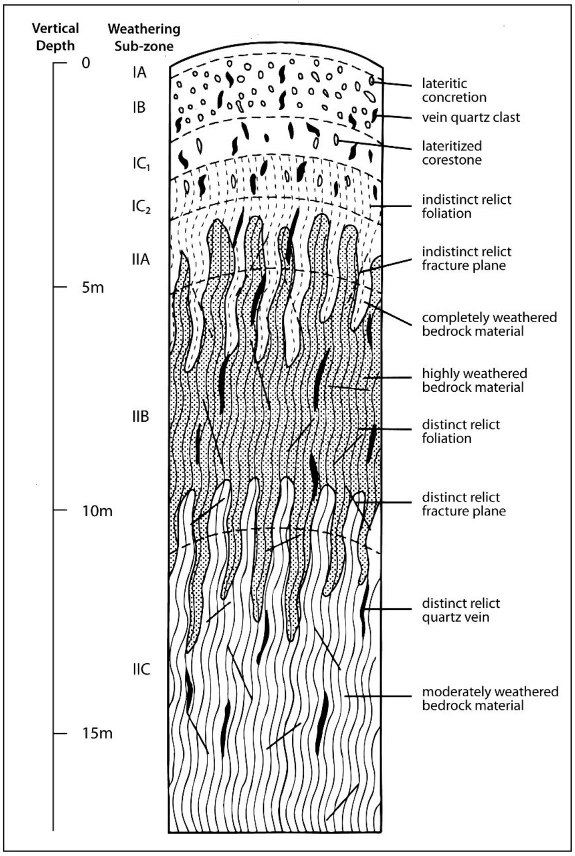

Figure 3: Schematic sketch of pedological and geological features in weathering profile.

and lateritized core-stones. The absence, or presence, of indistinct relict foliation planes furthermore, allows separation of the IC horizon into upper IC1, and lower IC2, sub-zones, respectively (Table 1 and Figure 3).

The saprock (henceforth known as zone II) is more than 16.2 m thick and consists of steeply dipping to vertical, alternating bands of white to light grey and pinkish to yellowish red, firm to stiff and hard, clayey silts and silts that indistinctly to distinctly preserve the minerals, textures and structures of the original schist bedrock material and mass. Bands of reddish yellow, firm clayey silt with indistinct relict foliation are prominent in the upper part of zone II and thus considered to represent completely weathered quartz-mica schist. Bands of white to light grey, hard silt with distinct relict foliation are prominent in the lower part of zone II and thus considered to represent moderately weathered quartz-mica schist. Bands of pinkish to grey, stiff silt with distinct relict foliation, are prominent in the middle of zone II and thus considered to represent highly weathered quartz-mica schist (Table 1 and Figure 3).

Lateral variations with depth in distribution of the bands of differently weathered schist, and preservation of fracture planes furthermore, allow Zone II to be differentiated into three sub-zones (Table 1 and Figure 3). The top IIA sub-zone is 2.2 m thick with indistinct relict fracture planes and comprises thick bands of completely weathered schist inter-fingering with thin bands of highly weathered schist; the completely weathered schist covering >50% by area. The intermediate IIB sub-zone is 7.7 m thick with indistinct to distinct relict fracture planes and consists of thick bands of highly weathered schist inter-fingering with thin bands of completely weathered schist; the highly weathered schist covering >70% by area. Thin bands of moderately weathered schist are also found inter-fingering with thick bands of highly weathered schist towards the bottom of sub-zone IIB. The lower IIC sub-zone is more than 6.3 m thick with distinct relict fracture planes and consists predominantly of thick bands of moderately weathered schist inter-fingering with thin bands of highly weathered schist; the moderately weathered schist covering >70% by area.

Physical properties of earth materials in the weathering profile

The earth materials show variations in physical properties that demarcate the different weathering sub-zones and reflect the increasing effects of weathering processes up the profile. Dry density ranges from 1,555 to 1,850 kg/m^3 and the dry unit weight from 15.25 to 18.15 kN/m^3 (Table 2). The zone II samples furthermore, show a general increase in dry density and unit weight with depth indicating decreasing density with increasing effects of weathering. The zone I samples, however, have more variable density and unit weights; the saprolite (sub-zone IC) having the maximum values of density and unit weight.

The specific gravity of soil particles is of limited variation; those of zone I ranging from 2.60 to 2.72, and those of zone II from 2.69 to 2.72 (Table 2). This limited variation is not unexpected in view of the closely similar range in specific gravity of the main mineral grains present. In zone I, the main minerals present are quartz with a specific gravity of 2.65, kaolinite with a specific gravity between 2.61 and 2.68, and sericite with a specific gravity between 2.77 and 2.88, whilst in Zone II there is in addition, illite with a specific gravity between 2.60 and 2.90 (Deer *et al.*, 1992).

Porosity is quite variable; the zone I samples with values of 32% to 40% and those of zone II from 29% to 34% (Table 2). Void ratios are similarly variable; the zone I samples with values of 0.48 to 0.67, and those of zone II with values of 0.41 to 0.53. A general decrease in porosity and void ratio with depth in zone II furthermore, indicates increasing porosity with increasing effects of weathering.

Moisture contents are quite variable; the topmost soil horizon IA with the highest content (16.5%) and sub-zone IIC with the lowest contents (4.3% to 7.5%)

Table 2: Physical properties of earth materials in the weathering profile.

Sub-zone	Sample	Vert. Depth (m)	Dry Density (kg/m³)	Dry Unit Weight (kN/m³)	S.G. Particles	Porosity (%)	Void Ratio	Water Cnt (%)	Degree Saturate (%)
IA	1	0.23	1555	15.25	2.60	40	0.67	16.5	64
IB	2	0.47	1776	17.42	2.65	33	0.49	10.6	57
IB	3	0.70	1796	17.62	2.65	32	0.48	7.0	39
IB	4	0.93	1750	17.17	2.72	36	0.55	8.2	40
IB	5	1.63	1762	17.29	2.72	35	0.54	7.6	38
IC1	6	2.10	1835	18.00	2.72	33	0.48	9.3	52
IC2	7	2.57	1708	16.75	2.72	37	0.59	14.1	65
IC2	8	3.50	1827	17.93	2.70	32	0.48	7.8	44
IIA	9	4.20	1827	17.92	2.70	32	0.48	5.5	31
IIA	10	4.90	1850	18.15	2.69	31	0.45	12.0	71
IIB	11	6.07	1770	17.36	2.70	34	0.53	6.3	32
IIB	12	6.77	1830	17.95	2.70	32	0.48	4.1	23
IIB	13	7.47	1810	17.76	2.70	33	0.49	6.1	34
IIB	14	8.17	1756	17.23	2.70	35	0.54	11.6	58
IIB	15	9.34	1832	17.98	2.70	32	0.47	5.8	33
IIB	16	10.28	1833	17.98	2.70	32	0.47	8.0	46
IIB	17	10.74	1814	17.79	2.70	33	0.49	7.9	43
IIC	18	11.71	1802	17.68	2.70	33	0.50	7.5	41
IIC	19	12.64	1877	18.41	2.70	30	0.44	4.4	27
IIC	20	13.85	1888	18.52	2.70	30	0.43	4.4	28
IIC	21	15.05	1855	18.19	2.70	31	0.46	7.5	44
IIC	22	16.25	1912	18.76	2.70	29	0.41	5.5	36
IIC	23	17.45	1776	17.42	2.70	34	0.52	7.0	37

Note: S.G. refers to Specific Gravity

whilst the other sub-zones have intermediate contents (4.1% to 14.1%). Degrees of saturation furthermore, show an exactly similar pattern as that of moisture contents (Table 2).

Soil index properties of earth materials in the weathering profile

Distinct variations in particle sizes are seen; the zone I samples with large clay fractions (>21%), and the zone II samples with large silt fractions (>52%) (Table 3). Sand fractions are more variable; large contents (32% to 48%) only present in the IB soil horizon which also has relatively large gravel fractions (10% to 14%). The relatively large sand and gravel fractions of the IB soil horizon are due to pedological processes that have given rise to the many lateritic concretions present. Zone II samples have very low gravel contents (<4%), though the sand fractions are very variable (0% to 16%); large sand fractions reflecting the presence of quartz pods and veins.

The zone II samples furthermore, show a general increase in clay contents up the profile (10% to 23%) but a corresponding decrease in silt contents (90% to 52%).

Table 3: Soil index properties of earth materials in the weathering profile.

Sub-zone	Sample	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Plastic Limit (%)	Liquid Limit (%)	Textural Weathering Index (I_w)
IA	1	0	27	30	43	25.3	64.1	0.59
IB	2	13	48	10	29	25.5	69.7	0.74
IB	3	11	32	34	23	23.9	69.7	0.40
IB	4	14	40	22	24	21.8	49.8	0.52
IB	5	10	46	23	21	19.9	49.8	0.48
IC1	6	1	1	73	25	22.2	47.8	0.26
IC2	7	0	14	59	27	26.5	43.0	0.31
IC2	8	0	3	76	21	25.2	33.5	0.22
IIA	9	0	12	71	17	28.2	id	0.19
IIA	10	0	2	89	9	29.5	id	0.09
IIB	11	0	37	52	11	26.8	id	0.17
IIB	12	0	5	85	10	25.7	id	0.11
IIB	13	0	12	65	23	26.3	id	0.26
IIB	14	0	7	75	18	23.5	id	0.19
IIB	15	0	2	88	10	25.3	id	0.10
IIB	16	0	8	77	15	26.6	id	0.16
IIB	17	0	1	81	18	24.4	id	0.18
IIC	18	1	16	71	12	25.3	id	0.14
IIC	19	0	0	88	12	30.0	id	0.12
IIC	20	4	13	68	15	27.0	id	0.18
IIC	21	0	0	90	10	25.9	id	0.10
IIC	22	1	7	82	10	25.6	id	0.11
IIC	23	1	3	86	10	26.9	id	0.10

Note: id refers to indeterminate

Increasing effects of weathering are thus marked by a general decrease in particle size; this feature reflecting increasing disintegration of the silt sized particles (Table 3).

Variations in consistency limits are less distinctive; the zone I samples with lower plastic limits (19.9% to 26.5%) than those of zone II (23.5% to 30%) (Table 3). Liquid limits could also only be determined for the Zone I samples (33.5% to 69.7%); the large silt contents of the zone II samples preventing the proper excavation of grooves in the Atterberg Device standard method of test.

Ratios of clay to total clay and silt contents, i.e. the Textural Weathering Index of Raj (2018), distinctly increase up the profile and reflect the increasing effects of weathering processes (Table 3). The earth materials of zone I with their relatively large clay contents are marked by large values (>0.22) of the Index, whereas those of zone II with their large silt contents are marked by lower values (0.10 to 0.18). Abrupt variations of the Index are seen in the zone II samples and reflect the local presence of quartz pods and veins that give rise to relatively large sand fractions.

Later stages of weathering of quartz-mica schist

The constant volume samples also show the moderately, highly, and completely, weathered quartz-mica schist (earlier defined from differences in colour and preservation of original minerals, textures and structures) to be characterized by differences in physical and soil index properties (Table 4). It is to be noted that these stages of weathering all involve *soil* material for the term *soil* is here considered to be *a natural aggregate of mineral grains that can be separated by such gentle means as agitation in water* (Terzaghi & Peck, 1948).

Binocular microscope examination of the silt fractions of the different stages of weathering shows them to consist exclusively of sericite flakes, whilst their sand fractions comprise fine quartz grains with some secondary iron oxide grains in highly and completely weathered schist (Table 4). Clay minerals in the different stages of weathering are variable; illite only present in moderately weathered schist but kaolinite and illite in highly weathered schist, and kaolinite with randomly interstratified illite-montmorillonite in completely weathered schist and pedological soil (Raj, 1993). Disintegration of muscovites and sericites in the original schist bedrock was thus considered to initially result in illite which was later transformed to kaolinite and randomly interstratified illite-montmorillonite through leaching (Raj, 1993).

DISCUSSION

Development of weathering profile

Differentiation of the pedological soil and saprock zones supports the view of Carroll (1970) that chemical weathering at the outer part of the lithosphere takes place in two stages; the first stage being the production of rotten rocks, on which the second stage, soil formation, takes place. The first stage is geochemical weathering, and is mostly the inorganic alteration of solid rocks, but in the second stage the effects of vegetation, both living and dead, together with the effects of metabolism of micro-organisms living in the geochemically altered rock materials, are added by the continued inorganic processes (Carroll, 1970). The pedological soil (zone I) is thus considered to result from alteration of the schist bedrock by both geochemical and pedological processes, whilst the saprock (zone II) results from inorganic alteration of the bedrock.

Recognition of these different processes is important, for a study of three deep weathering profiles over basalt, granite and schist (with depths to bedrock of 16, 27 and 10 m, respectively) showed them to have rather similar physico-chemical properties, despite differences in parent material (Hamdan & Burnham, 1997). Clay contents for instance, showed a decreasing trend with depth in all three profiles, whilst silt and sand contents showed an increasing trend with depth. Hamdan & Burnham (1997) thus concluded that the rain forests of the Peninsula over the old, deeply weathered soils had closed nutrient cycling systems where the cationic nutrients are in equilibrium with the main input from the atmosphere; there being negligible contribution of nutrients from weathering of bedrock.

The development of the weathering profile thus needs to take into consideration the geological history of the site and surrounding area. The present-day undulating terrain of low hills and ridges with meandering flat-bottomed valleys is clearly the result of down-cutting (incision) and lateral erosion by perennial rivers over eons of geological time. Down-cutting by rivers and the creation of valleys will give rise to a downward migration of unconfined groundwater tables in the adjacent hills and ridges. Lowering of the groundwater table will give rise to decomposition of the schist bedrock through various chemical reactions as hydrolysis, solution and the leaching of cations and anions. Lowering of the groundwater table

Table 4: Later stages of weathering of quartz-mica schist rock material.

Stage of weathering	Features
Completely weathered quartz-mica schist	Reddish yellow, firm clayey silt with yellow mottles and indistinct relict foliation. Material slowly disaggregates when dry samples are agitated in water. Coarse fraction of sericite flakes with some quartz and secondary iron oxide grains. Clay fraction of kaolinite and randomly interstratified illite-montmorillonite. Dry density 1.80 - 1.85 g/cc. Porosity 33 - 38%.
Highly weathered quartz-mica schist	Pinkish to grey, stiff silt with distinct relict foliation. Material readily disaggregates when dry samples are agitated in water. Coarse fraction of sericite flakes with some quartz and secondary iron oxide grains. Clay fraction of kaolinite and illite with some randomly interstratified illite-montmorillonite. Dry density 1.75 - 1.85 g/cc. Porosity 32 - 35%.
Moderately weathered quartz-mica schist	White to light grey, hard silt with distinct relict foliation. Material disaggregates when dry samples are agitated in water. Coarse fraction of sericite flakes with some quartz grains. Clay fraction of mainly illite with some poorly crystallized kaolinite. Dry density 1.80 - 1.92 g/cc. Porosity 29 - 33%.

also results in zones of aeration where other weathering reactions as oxidation and dehydration can occur.

Denudational processes (involving weathering and erosion) will give rise to decreasing overburden pressures on bedrock at depth and thus result in dilation (opening-up) along structural discontinuity planes, as foliation and fracture planes, in the schist bedrock. The overall impact of all these processes will be the disintegration and decomposition of the quartz-mica schists to variable depths below the ground surface.

Fluctuations in unconfined groundwater tables have also occurred in the area with deposition of alluvial sediments and formation of flat-bottomed valleys during aggradation as a likely result of Quaternary global sea-level changes (Raj, 2022). Softening and weathering of the schist bedrock will thus extend to considerable depths and account for the continuous weathering of meta-sedimentary bedrock to form residual soils and the total absence of fresh schist bedrock at surface outcrops; features earlier noted by Komoo & Mogana (1988).

Assignment of rock mass weathering grades or classes

Assigning rock mass weathering grades (IAEG, 1981; ISRM, 1981) or classes (ISRM, 2007) to the investigated weathering profile is difficult as the absence of fresh bedrock prevents definition of the boundary between rock and soil and does not allow use of *rock/soil* ratios (Komoo & Mogana, 1988). The pedological soil zone differentiated in this study (comprising sub-zones IA, IB and IC), however, can be directly correlated with rock mass weathering grade (or class) VI of the said schemes of classification (Table 5).

Minor differences in mineral compositions of the silt and sand fractions of the different stages of schist weathering indicate that there have only been minor mineralogical changes during weathering (Table 4). This is not unexpected for the main minerals in the original schist bedrock (ie. muscovite, sericite, quartz and graphite) are relatively stable under atmospheric conditions (Price, 1995). Disintegration of the muscovites

Table 5: Rock mass weathering class (ISRM, 2007) and weathering sub-zones.

Rock Class	Sub-zone	Thickness (m)	Pedological & Geological Features
VI	IA	0.4	Yellowish red, firm clay with some roots and burrows.
	IB	1.9	Red, firm clayey sand with abundant gravel sized lateritic concretions. Some lateritized core-stones and vein quartz clasts. Few roots.
	IC1	1.3	Reddish yellow, stiff, clayey silt with some yellow mottles. Some gravel sized vein quartz clasts and lateritized core-stones.
V	IC2	1.2	Reddish yellow, firm clayey silt with some yellow mottles. Many gravel sized lateritized core-stones and vein quartz clasts. Distinct relict quartz veins and pods. Indistinct relict foliation. (Completely weathered schist).
	IIA	2.2	Thick bands and wedges of reddish yellow, firm clayey silt with indistinct relict foliation (Completely weathered quartz-mica schist) alternating with thin bands of pinkish to grey, stiff silt with distinct relict foliation (Highly weathered quartz-mica schist). Distinct relict quartz veins and pods. Indistinct to distinct relict fracture planes. Some secondary iron stains and concretions along relict fracture planes. (Completely weathered schist >50% by area).
IV	IIB	7.7	Thick bands of pinkish to grey, stiff silt (Highly weathered quartz-mica schist) alternating with thin bands of reddish yellow, firm clayey silt (Completely weathered quartz-mica schist). Towards bottom of sub-zone, some thin bands of white to light grey, hard silt (Moderately weathered quartz-mica schist). Distinct relict foliation and fracture planes as well as quartz veins and pods. Some iron concretions and stains along fracture planes. (Highly weathered schist >70% by area).
III	IIC	>6.3	Thick bands of white to light grey, hard silt (Moderately weathered quartz-mica schist) alternating with thin bands of pinkish to grey, stiff, silt (Highly weathered quartz-mica schist). Distinct relict foliation and fracture planes as well as quartz veins and pods. Rare secondary iron stains along fracture planes. (Moderately weathered schist >70% by area).

and sericites, however, has been considered to initially result in illite that was later transformed to kaolinite and randomly interstratified illite-montmorillonite through leaching (Raj, 1993). Physical processes of weathering (ie. disintegration) are thus considered to be responsible for initial breakdown of the schist bedrock with further decomposition through leaching.

Notwithstanding the absence of fresh bedrock, recognition of the role of disintegration in weathering of the schist indicates that weathering sub-zones IIC, IIB and IIA (together with IC2) are best correlated with Classes III, IV and V, respectively, of the International Society for Rock Mechanics scheme for classification and description of rock mass (ISRM, 2007) (Table 5). The weathering zones and sub-zones differentiated in this study are thus equivalent to the weathering classes (as well as grades) of existing schemes for classification and description of rock mass.

CONCLUSIONS

It is concluded that pedological and geological features of the exposed earth materials, in particular the indistinct to distinct preservation of the minerals, textures and structures of the original schist, that allowed for characterization of the weathering profile. Two broad weathering zones were differentiated; an upper, 4.8 m thick, pedological soil (zone I) and a lower, >16.2 m thick, saprock (zone II). The pedological soil comprises thin IA and IB soil horizons of firm, clayey sand with lateritic concretions, and a IC soil horizon of stiff, clayey silt with quartz clasts and lateritized core-stones. The saprock (zone II) comprises steeply dipping to vertical, bands of pinkish to grey, stiff silt with distinct relict foliation (highly weathered schist) that inter-finger with bands of reddish yellow, firm clayey silt with indistinct foliation (completely weathered schist) towards the top (of zone II), and bands of white to light grey, hard silt with distinct foliation (moderately weathered schist) towards the bottom. Lateral variations in abundance of the differently weathered schist and preservation of fracture planes allowed zone II to be separated into IIA, IIB and IIC sub-zones.

Silt fractions in the weathering profile consist predominantly of sericite flakes, whilst the sand fractions are mostly of quartz grains and the clay fractions of mainly illite and kaolinite. Decreasing densities, unit weights and silt contents up the profile, but increasing porosities and clay contents, indicate increasing in situ alteration of the bedrock. Recognition of disintegration as a weathering process allowed the pedological soil (zone I) to be correlated with Class VI of standard rock mass weathering classifications, whilst the saprock sub-zones IIA, IIB and IIC are correlated with Classes V, IV and III, respectively. Lowering of an unconfined groundwater table as a result of down-cutting by rivers in adjacent valleys is considered responsible for development of the weathering profile.

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CONFLICT OF INTEREST

The author has no conflict of interest to declare that are relevant to the content of this article.

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