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Characterizing a weathering profile over the Kuantan Basalt

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Abstract: Three broad morphological zones can be differentiated; the top pedological soil (Zone I) being 3.60 m thick and comprising brown, soft to stiff, clays. The intermediate saprock (Zone II) is 1.12 m thick and consists of brown, very stiff, sandy silt with many lateritic concretions, whilst the bottom bedrock (Zone III) is an outcrop of vesicular olivine basalt with weathering along joints. Constant volume samples show the saprolite (sub-zone IC) to have dry unit weights of 11.78 to 12.80 kN/m^3, whilst the solum (sub-zones IA and IB), and saprock, have values ranging from 10.65 to 11.09, and from 11.35 to 11.50, kN/m^3, respectively. Porosities are variable; the saprolite with the lowest values of 52 to 56% and the solum and saprock with values of 57 to 60%. Clay and silt contents increase up the profile with a corresponding decrease in sand and gravel contents. Colloid (<1 μm size) contents especially increase up the profile from 10 to 15% in saprock through 30 to 40% in saprolite and exceeding 57% in the solum, These increasing colloid contents point to the increasing effects of pedological processes. Thin-sections of weathered rims (1-2 cm thick) show alteration of basalt to start with formation of micro-cracks (Stage 1) that become stained by secondary iron oxides and hydroxides. Decomposition of the essential minerals then occurs in the order: olivine (Stage 2), augite (Stage 3), and plagioclase feldspar (Stage 4). An increase in apparent porosity, but a decrease in unit weights and specific gravity, reflect these stages of weathering; the boundary between 'rock' and 'soil' material occurring when all olivine and augite crystals have decomposed. It is concluded that the weathering profile results from *in situ* alteration of basalt due to lowering of an unconfined groundwater table; pedological processes giving rise to further alteration.

Keywords: Weathering profile, Kuantan Basalt, pedological soil, saprock

INTRODUCTION

Weathering profiles are found in most parts of the world and show variable patterns and thicknesses for the rates, depths and courses of weathering are influenced by several factors, including climatic, biotic, geomorphic, site, geologic and chronologic ones (Thomas, 1974). As weathering occurs *in situ*, the weathered materials accumulate at the sites of formation and give rise to thick mantles of weathered materials (or regoliths) over bedrock. The regoliths show differences in the extent of preservation of the minerals, textures and structures of the original bedrock; the vertical sequence of materials of different composition extending upwards to the ground surface from the unaltered bedrock below known as the weathering profile (Ollier, 1969). Deep weathering profiles are found in humid tropical Peninsular Malaysia as a result of favorable tectonic and environmental settings that have facilitated prolonged and pervasive chemical weathering throughout most of the Cenozoic Era (Raj, 2009).

Weathering profiles have been characterized in various ways; most emphasizing the presence of a number of zones and sub-zones whose recognition involves morphological criteria, akin to descriptions of agricultural soil profiles (FAO, 2006). Various criteria have been employed and include colour, the extent of preservation of original bedrock minerals, textures and structures, and the shape and percentage occurrence of litho-relicts (core-stones and core-boulders) (Ollier, 1969). In geo-technical literature, it has been noted that weathering often produces a recognizable profile; an appreciation of which leads not only to a better understanding of engineering performance, the grouping of samples and the development of geotechnical models, but also allows for the possibility of reducing the number of boreholes, and *in situ* and laboratory tests (Anon., 1995).

In Peninsular Malaysia, published work on the characterization of weathering profiles over basic igneous bedrock is limited to the study of a profile over the Kuantan Basalt (Hamdan *et al.*, 2000; 2003). The 15 m deep profile was first differentiated into several soil horizons (sub-zones) and three broad zones then identified, i.e. an upper pedological soil (some 10 m thick) comprising the solum and saprolite, an intermediate saprock (some 5 m thick), and the underlying bedrock (Hamdan *et al.*, 2000) . Drastic changes in physico-chemical parameters of 7 samples collected at different depths, as well as microscopic observations and x-ray diffraction analyses, led to the conclusion that weathering at the profile was intense and rapid. It was also proposed, that the bedrock minerals olivine and augite transformed to goethite and chlorite in the saprolite, and finally to goethite in the solum, whilst the plagioclase feldspars were transformed to kaolinite and gibbsite, in both the saprolite and solum (Hamdan *et al.*, 2003).

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Three deep weathering profiles over basalt, granite and schist (with depths to bedrock of 16, 27 and 10 m, respectively) furthermore, were reported to have rather similar physico-chemical properties, despite differences in parent material (Hamdan & Burnham, 1996). It was thus concluded that the rain forests of Peninsular Malaysia over old, deeply weathered soils, had 'closed' nutrient cycling systems where the cationic nutrients are in equilibrium with the main input from the atmosphere; the contribution of nutrients from weathering of bedrock material being negligible. It was also noted that these deep weathering profiles had thick saprolites (IC soil horizons) that are relatively poor in nutrients and thus only marginally suitable or even unsuitable for the cultivation of perennial crops (Hamdan & Burnham, 1997).

A study of the physico-chemical properties of 20 soil samples over basalt in the Kuantan area noted that they were mostly characterized by large moisture contents (>30%) and liquid limits (>50%), but low maximum dry densities (1.22 to 1.60 g/cm^3) in compaction tests (Tan, 1994). It was also noted that though three distinct layers of different colour could be distinguished at soil profiles in the field, there were no significant differences in their physico-chemical properties (Tan, 1996).

Weathered materials over basalt in the Kuantan area have been classified as "bauxitic soils" and said to have geotechnical properties that are different from those of "temperate" zone soils (Noorul Iqhlima *et al.*, 2019). Unconsolidated undrained triaxial tests on 15 samples of "bauxitic" soils from 3 different sites and representing various stages of weathering were reported to have values of undrained cohesion and friction angle that varied with moisture content (Noorul Iqhlima *et al.*, 2019).

In the early 1980's was carried out a study to characterize weathering profiles over different bedrock in Peninsular Malaysia in order to allow for a better understanding of the stability of slope cuts excavated in them (Raj, 1983). As a part of this study, was investigated a weathering profile developed over basalt in the Kuantan area. In this paper is described the characterization of the profile, based on field mapping and the visual differentiation of morphological zones and sub-zones followed by laboratory determination of their physical and index properties. Weathering of the bedrock was also investigated through the study of thin-sections and slices of the weathered rims around core-boulders.

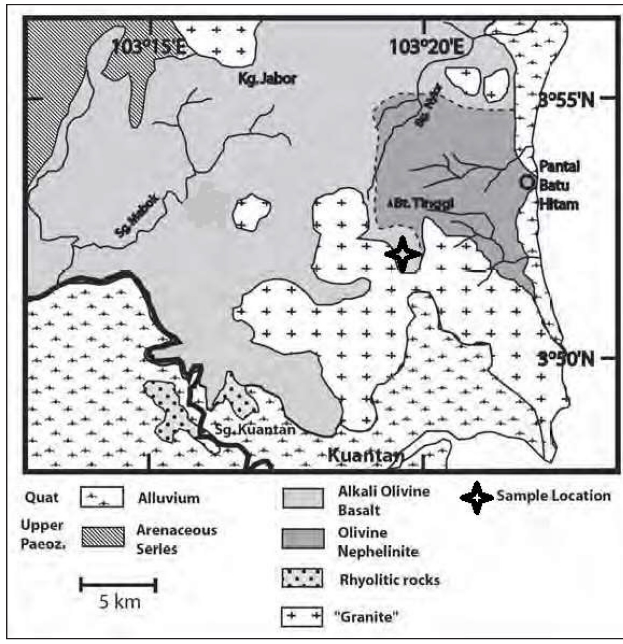

Figure 1: Geological sketch map of the Kuantan area, Pahang (after Azman & Nur Iskandar, 2007).

METHODOLOGY

The investigated weathering profile was exposed along the Kuantan - Jabor trunk road, close to the overhead bridge of the Kuantan Bypass Highway during excavation works for widening of the road shoulder (Figure 1). The cut is located on the side of a small valley with fresh basalt outcropping in the stream bed. Field mapping was first carried out to identify weathering zones and sub-zones, i.e. layers of earth materials with similar morphological features including colour, texture, concretions, relict bedrock structures and core-boulders. A total of ten constant volume samples (Numbers 1 to 10) were then collected at different depths for determination of the physical and index properties of the earth materials present (Figure 2 and 3). The samples were collected with brass tubes of 40 mm length and 76 mm internal diameter; the tubes having a constant wall thickness of 3 mm except at one end where the lower half tapered to a thickness of 1.5 mm to provide a cutting edge.

Moisture contents, unit weights and densities of the constant volume samples were determined before the specific gravity of the constituent mineral grains was measured using a pycnometer (GBRRL, 1959). Porosities, void ratios and degrees of saturation of the samples were calculated before the plastic and liquid limits of the fine fractions (<0.42 mm size) were determined according to standard methods (GBRRL, 1959). Particle size distributions of the samples were then determined using the sieving and sedimentation methods for the coarse (>0.0625 mm diameter) and fine grained fractions, respectively (GBRRL, 1959). X-ray diffractograms of the clay fractions were also prepared under normal, glycolated, and 500^{o}C heated, conditions to identify the minerals present (Thorez, 1975). It is to be noted that particle size limits follow the Wentworth (1922) Scale with gravel having diameters between 2 and 64 mm, sand, diameters between 0.625 and 2 mm, silt, diameters between 0.0039 and 0.0625 mm and clay, diameters less than 0.0039 mm.

Several samples (Numbers A1 to A12) of fresh basalt and weathered rims around core-boulders were also collected in the field for preparing thin-sections for microscopic study.

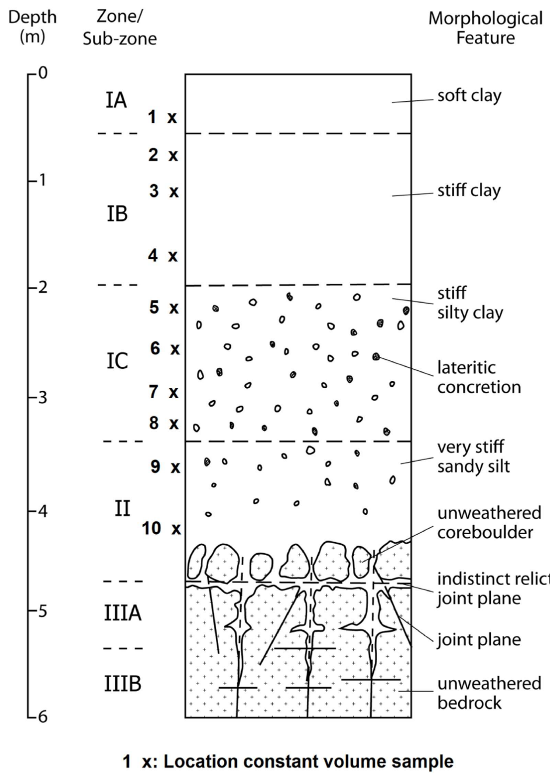

Figure 2: Schematic sketch of morphological features in the weathering profile with locations of constant volume samples (1 to 10).

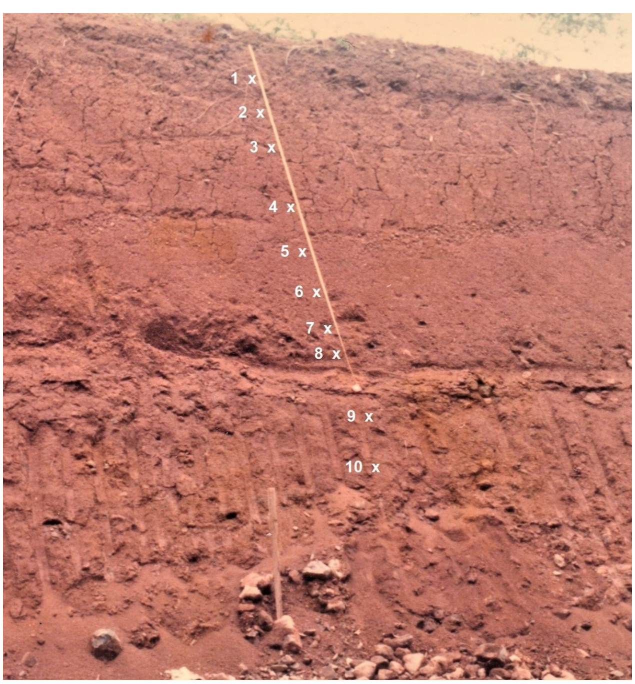

Figure 3: View of exposed weathering profile with locations of constant volume samples (1 to 10). (Tape is 3.90 m in length).

Thin slices of the weathered rims were diamond sawn for determination of densities, unit weights and apparent porosities employing the saturation and bouyancy technique of ISRM (1979), whilst the specific gravity of constituent mineral grains was measured using a pycnometer (GBRRL, 1959).

GEOLOGICAL SETTING OF WEATHERING PROFILE

Basaltic lavas and dolerite dykes in the Kuantan area were first mapped and described in detail by the Geological Survey of Malaysia (Fitch, 1951). The basaltic lavas, covering an area of some 125 km^2, overlie, and surround, granite hills to the N and NW of Kuantan, as well as overlie a sequence of Upper Palaeozoic sedimentary-volcanic rocks (Figure 1). The dolerite dykes, ranging in thickness from 2 cm to about 5 m, mainly trend NE to E and intrude the Upper Palaeozoic and granitic rocks. The basaltic lavas are considered to result from fissure type eruptions; the center of extrusion near Bukit Tinggi, which at an elevation of 138 m above sea level, is the highest point where the basalts are found (Fitch, 1951). The basalts have also been considered to result from a central volcanic vent type eruption; the vent located at Bukit Tinggi (Bignell, 1972). Field mapping of the basalt furthermore, yielded palaeo-flow directions that indicate the presence of two vents; one at Bukit Tinggi, and another at a hill located 1.9 km NW of Bukit Ubi (Raj, 1990).

The dolerite dykes were first considered as feeder fissures to the basaltic lavas, though K-Ar dating of a dyke sample at 111 $\pm$ 4 Ma, and a basalt sample at 1.6 $\pm$ 0.2 Ma, indicated a long time interval between the two igneous events (Bignell & Snelling, 1977). The dolerite dykes and basaltic lavas furthermore, differ in petrology, age and palaeo-magnetic directions, and are thus not genetically related (Haile *et al*., 1983). Several K-Ar radiometric dates yielding an average age of 1.7 $\pm$ 0.2 Ma clearly indicate the Quaternary occurrence of the Kuantan Basalt (Bignell & Snelling, 1977).

Initial work classified the Kuantan Basalt as an olivine basalt, both with and without nepheline (Fitch, 1951). A detailed study of thin-sections and several chemical analyses, however, concluded that the Kuantan Basalt involved two distinct and perhaps independent magma types, namely alkali olivine basalt magma and olivine nephelinite magma (Chakraborty, 1977). The olivine basalts were largely present in the western part of the Kuantan area, whilst the olivine nephelinites were restricted to the eastern part. The sequence of eruptions is not known, though olivine nephelinite appeared, at least in part, to be later than olivine basalt (Chakraborty, 1979).

A study of trace elements in the Kuantan Basalt noted that the olivine basalt and olivine nephelinite are both enriched in incompatible and light rare earth elements; signatures comparable with Oceanic Island basalts and East African Rift basaltoids. It was thus concluded that the geochemical evidence, as well as the timing, pointed to a mantle plume-related genesis for the Kuantan Basalt, rather than one related to wrench tectonics-induced extension (Azman & Nur Iskandar, 2007).

At the investigated weathering profile, the exposed bedrock is a black to dark green, micro-crystalline, vesicular olivine basalt with horizontal and vertical joints. In thin-sections, the basalt is seen to be composed of calcic plagioclase, augite, olivine, magnetite and limonite. The texture is normally inter-granular with augite crystals occupying the spaces between plagioclase laths. Sub-ophitic textures are also seen in some coarser grained varieties where the euhedral phenocrysts show little or no corrosion and consist mainly of olivine and rarely of plagioclase.

RESULTS

Morphological zones and sub-zones in the weathering profile

Vertical variations in colour, texture and preservation of original bedrock structures allowed differentiation of three broad zones; an upper pedological soil (Zone I), an intermediate saprock (Zone II), and the underlying bedrock (Zone III) (Table 1 and Figure 2). These zones are developed approximately parallel to the overlying ground surface and are similar to the zones differentiated in the earlier study of another weathering profile over the Kuantan Basalt (Hamdan *et al*., 2000; 2003).

The pedological soil is 3.6 m thick and can be separated into IA, IB and IC soil horizons (sub-zones); the IA and IB horizons constituting the solum, and the IC horizon, the saprolite (Table 1). The IA and IB horizons are relatively thin and comprise soft to stiff, brown clays, whilst horizon IC is 1.52 m thick and consists of a stiff, brown silty clay with many lateritic concretions.

The saprock is only 1.12 m thick and consists of a very stiff, brown sandy silt with many gravel sized lateritic concretions and a few core-boulders towards its bottom (Table 1). The bedrock is a continuous outcrop of basalt and can be separated into an upper sub-zone (IIIA) with effects of weathering along and between joint planes, and a lower sub-zone (IIIB) with effects of weathering along joint planes (Table 1).

Seepage was not observed at the time of investigation, though an unconfined groundwater table is expected at shallow depth in view of the adjacent perennial stream whose bed is some 5 m vertically below the road shoulder level.

Physical properties of earth materials in the weathering profile:

Constant volume samples show the earth materials to be rather loose; horizons IA and IB having dry unit weights of 10.65 to 11.09 kN/m^3, whilst horizon IC, and Zone II, have values of 11.78 to 12.90, and 11.35 to 11.50, kN/m^3, respectively (Table 2). Values of dry density mirror those of dry unit weight; horizons IA and IB having values of 1,086 to 1,130 kg/m^3, horizon IC, 1,201 to 1,305 kg/m^3, and Zone II, 1,157 to 1,172 kg/m^3 (Table 2).

The specific gravity of soil particles is relatively constant with those of horizons IA and IB having values between 2.69 and 2.73 (Table 2). The specific gravity of soil particles from horizon IC and Zone II is, however, slightly higher from 2.73 to 2.76 in view of the lateritic concretions that are present. The porosity of the earth materials is relatively high; horizons IA and IB having porosities of 58 to 60%, whilst Zone II and horizon IC have porosities between 52% and 58% (Table 2). Void ratios are reflective of the large porosities with horizons IA, IB and Zone II, having ratios between 1.35 and 1.48, whilst horizon IC has a void ratio between 1.09 and 1.22.

Field moisture contents have limited variation within the profile with values between 35% and 47% (Table 2). Degrees of saturation are high with samples from horizons IA and IB having values of 87.8% to 91.8%, whilst those

Table 1: Field description of morphological zones and sub-zones in the weathering profile.

Zone & Sub-zone	Depth (m)	Field Description
IA	0.00 - 0.60	Brown (7.5YR4/4), soft clay; porous; crumbly dry; many roots; some burrows; boundary wavy, diffuse
IB	0.60 - 2.08	Brown (7.5YR4/4), stiff clay; sub-angular blocky moist; friable dry; some large roots; few burrows; boundary wavy, diffuse
IC (Saprolite)	2.08 - 3.60	Brown (7.5YR4/4), stiff silty clay; sub-angular blocky moist; many lateritic concretions; boundary wavy, clear.
II (Saprock)	3.60 - 4.72	Brown (7.5YR4/4), very stiff, sandy silt; many gravel sized, lateritic concretions; sub-angular blocky moist; core-boulders in lower part; indistinct relict joint planes; boundary irregular, diffuse
IIIA (Bedrock)	4.72 - 6.61	Basalt with weathering (staining & alteration to sandy silt) along and between discontinuity planes; boundary irregular, diffuse
IIIB (Bedrock)	>6.61	Basalt outcrop with effects of weathering only along discontinuity planes only.

Note: Colour based on Munsell Colour Chart from horizon IC, and Zone II, have values between 88.2% and 95.0%. The high degrees of saturation in Zone II further support the inference of an unconfined groundwater table at shallow depth.

Index properties of earth materials in the weathering profile

Grain size analyses show distinct variations with depth; there being low sand and gravel contents (<13%) in horizons IA and IB, intermediate contents (11 to 27%) in horizon IC and fairly large contents (>35%) in Zone II (Table 3). Binocular microscope examination of the sand sized particles shows them to be mostly dark brown in colour and thus likely to be secondary iron oxide grains. Silt contents also decrease up the profile with 31 to 43% in Zone II, but 23 to 37% in horizon IC, and 12 to 29% in horizons IA and IB (Table 3).

Clay contents distinctly increase up the weathering profile with Zone II having low contents (17 to 22%), whilst horizon IC has moderate contents (35 to 48%) and horizons IA and IB, large contents (>60%) (Table 3). Fine clay (<2 μm size) contents especially, increase up the profile with low contents (<19%) in Zone II, moderate contents (35 to 48%) in horizon IC, and large conents (61 to 71%) in horizons IA and IB (Table 3). Colloid (<1 μm size) contents mirror the increase in fine clay contents up the profile with low contents (13 to 19%) in Zone II, moderate contents (35 to 48%) in horizon IC and large contents (61 to 71%) in horizons IA and IB (Table 3). Increasing fine clay and colloid contents up the profile, especially within Zone I, clearly indicate the role of pedological processes in the continued disintegration and disaggregation of altered (weathered) bedrock.

Plastic limits show some variation within the profile; horizons IA and IB having values between 44.3 and 51.8%,

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

Constant Volume Sample	Zone/ Sub-Zone	Depth (m)	Dry Unit Weight (kN/m³)	Dry Density (kg/m³)	Porosity (%)	SG Particles	Moisture Content (%)	Degree Saturation (%)
1	IA	0.43	10.65	1,086	59.6	2.69	48.2	87.8
2	IB	0.78	10.80	1,101	59.7	2.73	49.0	90.4
3	IB	1.07	10.83	1,104	59.6	2.73	48.6	90.1
4	IB	1.68	11.09	1,130	58.1	2.70	47.2	91.8
5	IC	2.14	12.80	1,305	52.2	2.73	35.3	88.2
6	IC	2.65	12.36	1,260	53.8	2.73	39.5	92.5
7	IC	3.00	12.18	1,242	55.0	2.76	41.1	92.8
8	IC	3.27	11.78	1,201	56.0	2.73	44.3	95.0
9	II	3.82	11.35	1,157	58.1	2.76	46.0	91.6
10	II	4.36	11.50	1,172	57.4	2.75	45.0	92.0

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

Constant Volume Sample	Zone/ Sub-zone	Gravel (%)	Sand (%)	Silt (%)	Total Clay (%)	Fine Clay (%)	Colloids (%)	Plastic Limit (%)	Liquid Limit (%)
1	IA	0.0	6.8	29.2	64	61	57	44.3	70.0
2	IB	0.2	7.8	16.0	76	73	68	48.7	70.0
3	IB	1.9	11.9	12.2	74	71	66	51.8	70.0
4	IB	1.2	7.2	19.6	72	70	68	49.6	68.0
5	IC	3.2	26.0	22.8	48	43	39	44.7	66.0
6	IC	5.2	22.7	34.1	38	35	30	42.2	63.5
7	IC	4.3	23.0	22.7	50	46	40	44.9	65.0
8	IC	0.8	10.0	37.2	52	48	42	45.6	63.0
9	II	14.2	37.5	31.3	17	13	10	40.6	63.0
10	II	7.8	27.1	43.1	22	19	15	40.6	-

Note: Fine clay <2 μm size; Colloids <1 μm size whilst horizon IC and Zone II, have values between 40.6 and 45.6 % (Table 3). Liquid limits also show some variation with horizons IA and IB having values of 68 to 70%, whilst horizon IC and Zone II, have values between 63 and 66% (Table 3). In view of these results, the earth materials of the weathering profile all plot below the "A line" in the Plasticity Chart of the Unified Soil Classification System and are thus classified as silty to sandy clays (Wagner, 1957).

X-ray diffractograms show kaolinite to be the predominant clay mineral present; its identification based on the narrow, symmetrical peaks at 12.30° 2θ (7.20 Å) and 24.80° 2θ (3.59 Å) on the untreated scans that do not shift in the glycolated scans but disappear in the 500°C heated scans (Figure 4). The saprock (Zone II) samples, however, indicate the presence of disordered kaolinite in view of the broad low peaks at about 12.30° (7.20 Å) and 24.80° 2θ (3.59 Å) on the untreated scans (Thorez, 1974). Increasing ordering of kaolinite up the weathering profile is indicated by increased intensities and clearer definition of the reflection peaks at 12.30° (7.20 Å) and 24.80° 2θ (3.59 Å) 2θ. Goethite is also present in the clay sized fraction and identified by the broad reflection at 21.75° 2θ (4.18 Å) in the untreated scans. It is to be noted that the diffractograms have a substantial background that results from the large colloid contents present.

Weathering of basalt rock material

Hand specimens and thin-sections of the narrow (1-2 cm tick), weathered rims around core-boulders show that weathering (alteration) of the basalt can be separated into a number of generalized stages (Table 4). Weathering starts with the formation of micro-cracks that become stained by secondary iron oxides and hydroxides (Stage 1). This is then followed by successive decomposition of the essential minerals in the order of olivine (Stage 2), augite (Stage 3) and plagioclase feldspar (Stage 4). Olivine and augite are transformed into chlorite and clay minerals, whilst the plagioclase feldspars are transformed into kaolinite and gibbsite (Table 4). Identifiable magnetite, ilmenite and epidote grains are also seen in thin-sections in the early stages of weathering.

The changes in fabric and successive decomposition of the essential minerals is reflected by variations in physical properties; increasing stages of weathering marked by a decrease in dry unit weights and an increase in apparent porosity (Table 5). It is to be noted that weathered basalt can no longer be considered as a coherent, "rock" material when the essential minerals olivine and augite have all been decomposed (Stage 4). This transition between basalt "rock" and "soil" occurs over very narrow distances (1-2 cm) and there is thus an abrupt boundary between core-boulders and the enveloping soil. In the earlier study on another weathering profile over the Kuantan Basalt (Hamdan *et al.*, 2003), it was pointed out that intense weathering had already occurred at the early stage of alteration of basalt with several weathering indices indicating a very drastic change in the saprock zone. It was thus stated that basalt transformed directly into saprolite due to its' high weatherability under humid tropical conditions (Hamdan *et al.*, 2003).

An interesting feature in the weathering of the basalt rock material is the decrease in specific gravity with increasing alteration (Table 5). The fairly large specific gravity (2.83 to 2.87) of the fresh basalt (Stage 0) is undoubtedly due to the presence of unaltered, olivine, and augite crystals, which have specific gravity values of between 3.2 and 4.4, and between 3.2 and 3.6, respectively (Deer *et al.*, 1977). Decreasing values of specific gravity thus indicate alteration of the olivine and augite crystals to chlorite and clay minerals, for chlorite has a specific gravity between 2.6 and 3.3 (Deer *et al.*, 1977). Fresh plagioclase feldspar crystals furthermore, have a specific

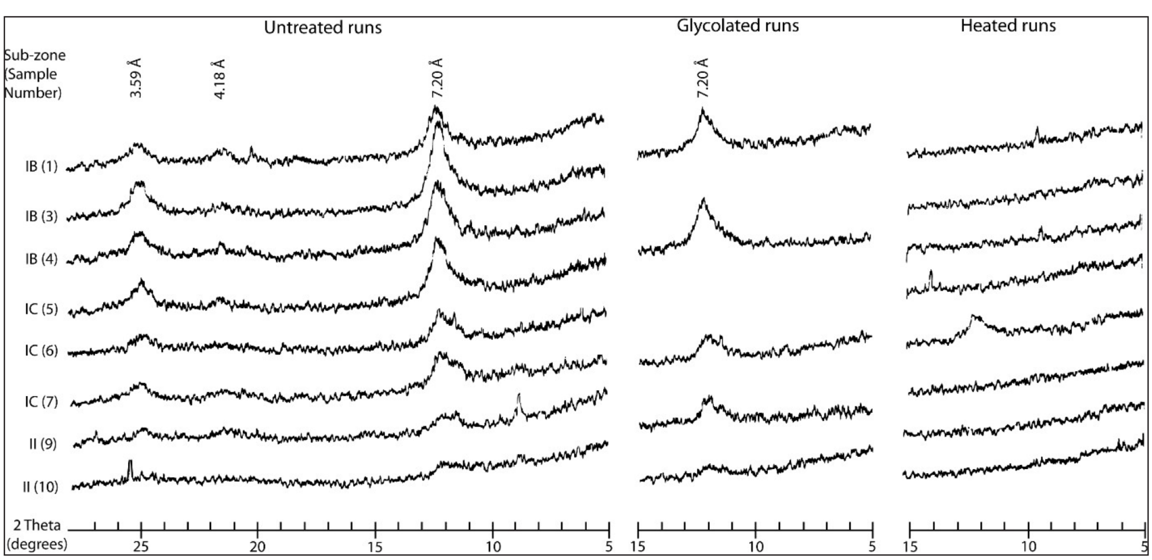

Figure 4: X-ray diffractograms of clay sized fractions in the weathering profile.

gravity of between 2.62 and 2.76, whilst kaolinite has a value between 2.58 and 2.63, and gibbsite a relatively low specific gravity of 2.35 to 2.40 (Deer *et al*., 1977).

DISCUSSION

The differentiation of three broad zones in the weathering profile is similar to that of the earlier study by Hamdan *et al.* (2000; 2003) and supports application of the pedo-weathering profile concept (Tandarich *et al.*, 2002). Differentiation of the three broad zones also substantiates 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

Table 4: Generalized stages of weathering of Kuantan Basalt (rock material).

Stage	Hand specimen description	Thin-section description
0	Black rock material. Mineral grains appear hard and fresh with vitreous lustres. (Unweathered).	Essential minerals (olivine, augite and plagioclase) appear fresh and unaltered. Magnetite, ilmenite and epidote grains seen.
1	Black rock material. Mineral grains appear hard and fresh with vitreous lustres. (Slightly weathered).	Several micro-cracks with essential minerals (olivine, augite and plagioclase) mostly fresh and unaltered. Iron oxide and hydroxide stains seen along some micro-cracks. Magnetite, ilmenite and epidote grains also seen.
2	Black rock material with isolated, brown spots and stains. Mineral grains appear hard and fresh with vitreous lustres. (Moderately weathered).	Many micro-cracks with secondary iron oxide and hydroxide stains. Olivine crystals all decomposed (to chlorite and clay minerals). Augite and plagioclase crystals appear fresh and unaltered. Magnetite, ilmenite and epidote grains also seen.
3	Grey rock material with brown stains. Mineral grains show vitreous to sub-vitreous lustres. (Highly weathered).	Many micro-cracks with secondary iron oxide and hydroxide stains. Augite crystals fissured and mostly altered (to clay minerals). Plagioclase crystals appear fresh and unaltered. Some magnetite, ilmenite and epidote grains seen.
4	Weak, brownish “rock” material. Disaggregates when agitated in water. (Completely weathered).	Olivine and augite crystals all altered (to clay minerals). Most plagioclase feldspars altered (to clay minerals). Many opaque minerals seen.
5	Brown, very stiff, sandy silt. Dis-aggregates when samples are agitated in water. (Soil material)	Essential minerals all altered to kaolinite and gibbsite (identified from X-ray diffractograms). Many opaque minerals.

Table 5: Physical properties of generalized stages of weathering of Kuantan Basalt (rock material).

Sample Number	Stage	Dry Unit Weight (kN/m^3)	Saturated Unit Weight (kN/m^3)	SG Particles	Apparent Porosity (%)
A1	0	27.10	27.52	2.83	2.3
A2	0	27.20	27.60	2.84	2.3
A3	0	27.51	27.82	2.87	2.3
A4	1/2	22.89	28.67	2.66	12.2
A5	1/2	22.79	24.43	2.69	13.6
A6	2	20.78	23.13	2.60	18.6
A7	2	20.72	23.02	2.59	18.5
A8	3	18.41	21.23	2.56	26.7
A9	3	16.02	19.57	2.47	33.8
A10	4	13.82	18.11	2.40	41.4
A11	4	13.40	17.68	2.44	44.1
A12	4	12.26	16.26	2.52	50.4

in the geochemically altered rock materials, are added by the continued inorganic processes (Carroll, 1970).

The pedological soil (Zone I) which comprises the solum (horizons IA and IB) and saprolite (horizon IC) is thus considered to result from alteration of bedrock by both geochemical and pedological processes, whilst the saprock (Zone II) results from alteration of bedrock by geochemical processes. The geochemical processes that occurred furthermore, result from gradual lowering of an unconfined groundwater table at the site due to down-cutting by the adjacent perennial stream during the Quaternary Period.

Increasing fine clay and colloid contents up the weathering profile, especially within Zone I (pedological soil) indicate the importance of pedological (soil forming) processes. In the earlier study of the weathering profile over the Kuantan Basalt, it was thus noted that the decrease in the silt to clay ratio from the saprolite up to the solum pointed to an increase in weathering and soil formation (Hamdan *et al.*, 2003).

An enigmatic feature of the weathering profile is the somewhat large content of sand and silt sized particles (31 to 43%) in the *saprock* (Zone II) for the basalt decomposes to mainly clay minerals (Table 4). An explanation for this discrepancy is most likely found in the many sand to gravel sized lateritic concretions present not only in the *saprolite*, but also in the *saprock*. It has also been suggested that there may be strong aggregation of clay by iron to form pseudo-sands and clay-balls; an explanation offered for the friable and fluffy consistency of *solum* layers observed in the field in the earlier cited study (Hamdan *et al.*, 2000).

CONCLUSION

Three broad zones have been differentiated in the weathering profile; an upper pedological soil (Zone I), an intermediate saprock (Zone II) and the underlying bedrock (Zone III). The 3.60 m thick, Zone I comprises brown, soft to stiff clays, and can be separated into soil horizons IA and IB (solum), as well as IC (saprolite). The 1.12 m thick saprock consists of brown, very stiff, sandy silt with many lateritic concretions, whilst Zone III is an outcrop of vesicular olivine basalt.

Constant volume samples show the saprolite to be the densest layer with dry unit weights of 11.78 to 12.80 kN/m^3 and apparent porosities of 52 to 56%. The solum and saprock have dry unit weights of 10.65 to 11.50 kN/m^3, and apparent porosities of 57 to 60%. Clay and silt contents increase up the profile with a corresponding decrease in sand and gravel contents. Colloid (<1 µm size) contents especially increase up the profile and indicate the increasing effects of pedological processes.

Weathered rims around core-boulders show alteration of the basalt to start with the formation of micro-cracks followed by decomposition of the essential minerals in the order: olivine, augite and plagioclase feldspar. These stages of weathering are marked by an increase in apparent porosity, but a decrease in unit weight and specific gravity; the boundary between 'rock' and 'soil' material occurring when all olivine and augite crystals have decomposed.

In situ alteration of the basalt is considered to result from the gradual lowering of the unconfined groundwater table at the site as a result of down-cutting by the adjacent perennial stream during the Quaternary Period.

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CONFLICT OF INTEREST

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

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