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Morphological characterization of a weathering profile over orthopyroxene rhyodacite in Malaysia

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Abstract: Variations in morphological features, considered to reflect differences in the extent of weathering of an orthopyroxene rhyodacite, allowed differentiation of two broad zones at the profile, i.e. an upper pedological soil (zone I), some 12.2 m thick of sandy clays, and a lower, >32.2 m thick, saprock (zone II) of silty sands with indistinct to distinct, relict bedrock textures and structures. The pedological soil comprises soil horizons A, B and C, whilst the saprock is separated into four sub-zones IIA, IIB, IIC and IID in view of differences in preservation of joint, banding and fault planes and the content of core-boulders. The exposed weathered bedrock materials have porosities of 39% to 53%, and dry densities of 1211 to 1574 kg/m^3, whilst the soil particles have a specific gravity between 2.57 and 2.62. Particle size distributions are variable with depth; the pedological soil with large clay (>27%) but low silt (<30%) fractions, and the saprock with large silt (>26%) but low clay (<26%), fractions. Sand fractions are variable (23-60%) and gravel fractions minimal (<9%). Increasing clay, but decreasing silt, fractions up the profile indicate increasing alteration of bedrock material; a feature reflected by increasing values of the textural weathering index (I_w). Weathering zone I (pedological soil) is correlated with grade, or class, VI of standard rock mass weathering classifications, whilst sub-zones IID and IIC are equated with grades, or classes, III, and IV, respectively, and sub-zones IIA and IIB with grade, or class, V. It is concluded that field differentiated, weathering zones and sub-zones can be equated with standard rock mass weathering grades or classes, and have the advantage that they allow recognition of indistinctly to distinctly preserved, relict bedrock structures.

Keywords: Orthopyroxene rhyodacite, weathering profile, pedological soil, saprock, rock mass weathering grade, rock mass class

INTRODUCTION

Weathering profiles have been characterized in various ways; most characterizations describing the presence of a number of zones and sub-zones whose recognition is based on morphological features such as the texture and color of weathered materials, the content of core-stones and core-boulders, and the degree of preservation of original bedrock textures and structures (Lan *et al*., 2003; Rahardjo *et al*., 2004; Leao & Marques, 2016; Alavi *et al*., 2016; Raj, 2018; Jaques *et al*., 2021; Bonnet *et al*., 2022; Bonnet *et al*., 2023; Raj, 2023). The zoning of weathering profiles over granitic bedrock furthermore, is said to have advanced from simple geological descriptions (or qualitative analyses) to more comprehensive analyses involving several physical and mechanical indices (quantitative analyses) (Lan *et al*., 2003). The zones and sub-zones that have been differentiated are layers that result from the operation of various "geological, pedological, hydrological and biological processes, or various combinations thereof; the term 'layer' referring to a more-or-less tabular body of unconsolidated material or rock that is roughly parallel to the land surface, or the surface on which it formed, and which is more or less distinctly limited above and below" (Phillips & Lorz, 2008).

Employing weathering zones and sub-zones for geotechnical purposes, however, has been criticized on the grounds that their differentiation is based on qualitative criteria (Dearman, 1976). Different stages of weathering of granitic bedrock material were then described, and it was proposed that the rock/soil ratio, the degree of discoloration and the presence or absence of original bedrock texture be employed to differentiate weathering grades in rock masses (Dearman, 1976). Several schemes have been proposed for assigning rock mass weathering grades; the more commonly employed ones being those proposed by IAEG (International Association of Engineering Geology) (1981), ISRM (International Society for Rock Mechanics) (1981), GCO (Geotechnical Control Office) (1988) and GSL (Geological Society of London) (1990). It is to be noted that classes are used instead of grades in more recent suggestions for classification and description of fresh and weathered rock masses (ISRM, 2007; ISRM, 2015).

The geotechnical characterization of a weathering profile over an orthopyroxene rhyodacite in Peninsular Malaysia is discussed in this article; field mapping first carried out to demarcate weathering zones and sub-zones based on morphological features such as color, particle sizes,

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and extent of preservation of original bedrock minerals, textures and structures, and the content of core-boulders. The weathering profile was then characterized in terms of the rock mass weathering grades of IAEG (1981), ISRM (1981) and GSL (1990), and finally characterized in terms of the rock mass classes described by ISRM (2007) and ISRM (2015). The three schemes of characterization were compared and conclusions reached on their applicability; emphasis being placed on recognition and mapping of relict bedrock structures.

Geological setting

The slope cut at Km 38.4 (east bound) of the Kuala Lumpur - Karak Highway (Figure 1) exposes a weathering profile developed over acidic igneous rocks that were first classified as porphyritic pyroxene micro-granodiorite (Liew, 1977; Haile *et al*., 1977). To the west, the micro-granodiorite appears to be in fault contact with an approximately NNW-SSE trending belt of acid volcanics, whilst to the east, it is separated by the NW-SE trending Bukit Tinggi Fault Zone from porphyritic biotite granite that has been mapped as the Bukit Tinggi Granite Pluton (Cobbing & Mallick, 1987).

More recent workers, however, describe the porphyritic pyroxene micro-granodiorite as being an orthopyroxene bearing rhyodacite porphry (or orthopyroxene rhyodacite) and the acid volcanics as orthopyroxene lacking rhyodacitic rocks (or rhyodacite) (Azman & Singh, 2005). These rhyodacites are considered to form the "Genting Sempah

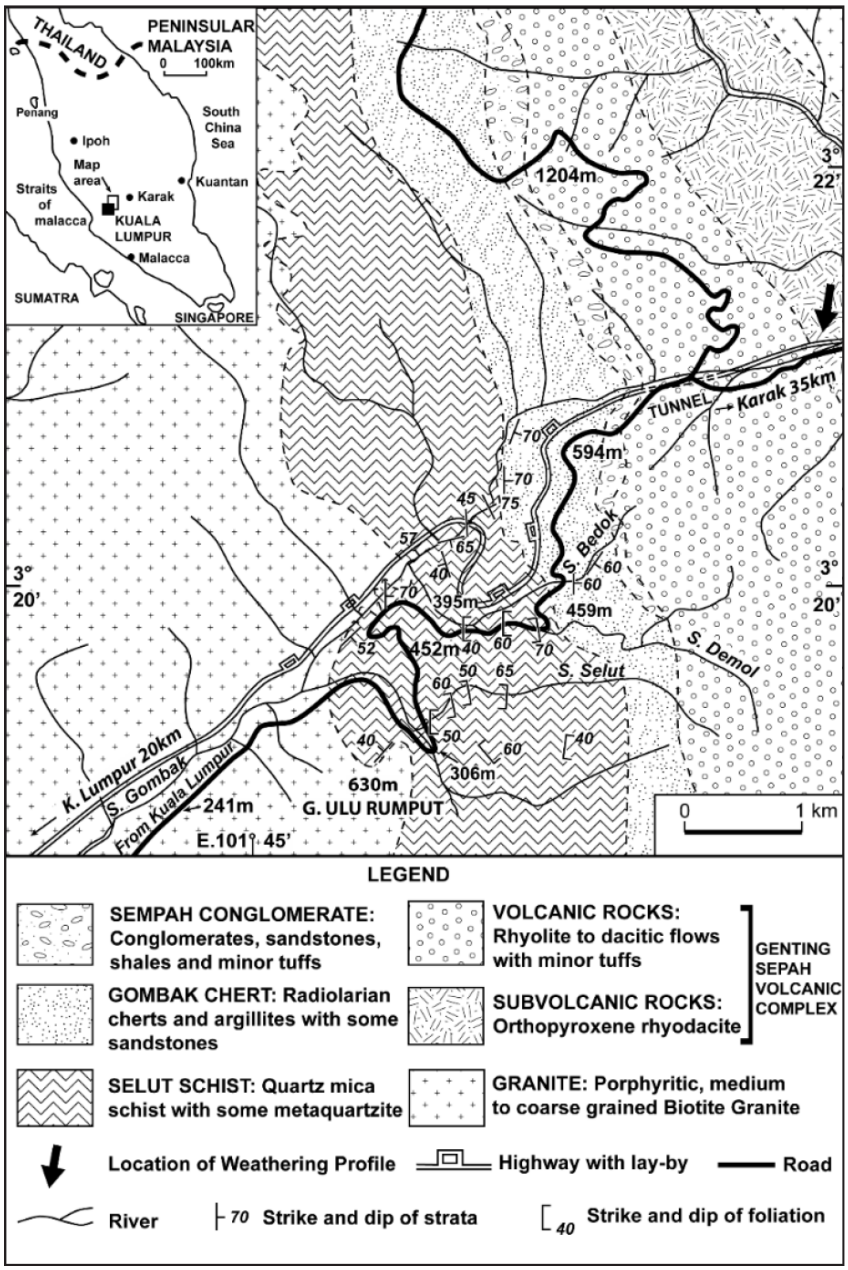


Figure 1: Geological setting of weathering profile (Haile *et al.*, 1977; Azman & Singh, 2005).

Volcanic Complex"; a Complex that is both spatially and temporally related to the Triassic Main Range Granite (Azman & Singh, 2005).

In thin-sections, the orthopyroxene rhyodacite is seen to be a porphyritic, hypidio-morphic, holocrystalline rock with phenocrysts (50-65%) of quartz, plagioclase, biotite, alkali feldspar and pyroxene (hypersthene) in a groundmass of quartz and alkali feldspar (Liew, 1977). Details on the mineralogical composition of the orthopyroxene rhyodacite are provided in Liew (1977) and Azman & Singh (2005).

Seepage was not seen at the slope cut (Figure 2) and indicates that any unconfined groundwater table present is located at greater depth. Bedrock exposures at nearby cuts and in river valleys show the orthopyroxene rhyodacite to be moderately to strongly jointed (0.2-0.7 m spacings) and cut by faults of variable orientations. An indistinct alignment of biotite flakes is also seen in the bedrock and gives rise to banding planes; the alignment suggesting magmatic flow in the volcanics which outcrop to the immediate west (Raj, 2018).

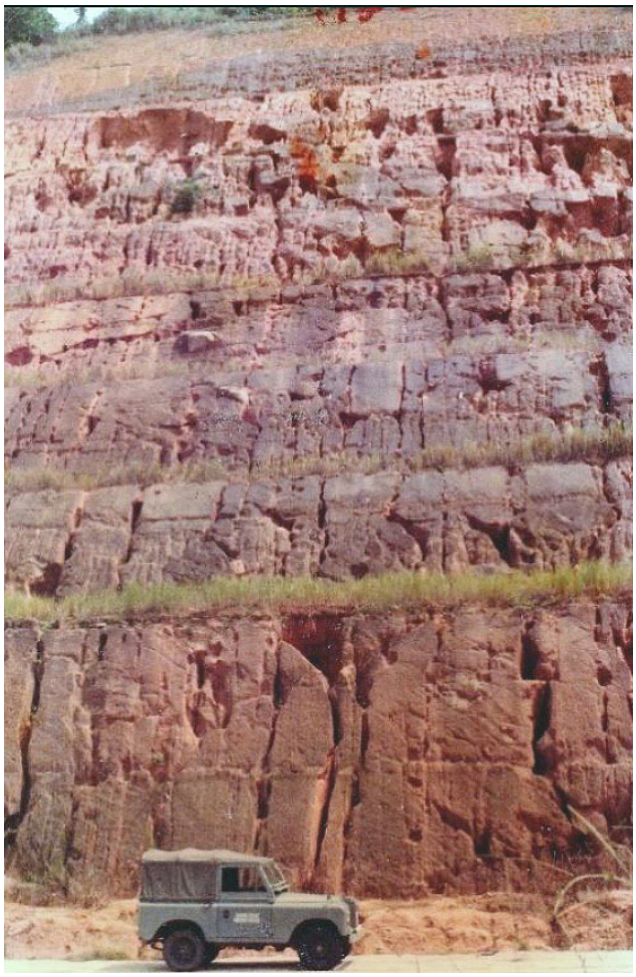


Figure 2: Slope cut exposing weathering profile over orthopyroxene rhyodacite.

METHODOLOGY

Site visits during excavation revealed a variety of earth materials ranging from moderately to highly and completely weathered bedrock as well as pedological soil and litho-relicts (i.e., core-stones and core-boulders). Field mapping therefore, was first carried out to characterize the exposed earth materials in geotechnical terms; large core-boulders (>0.5 m^3) being classified as rock, and all other earth materials (including pedological soil and moderately to highly and completely weathered bedrock) considered as soil. This classification of earth materials follows the guidelines of Jabatan Kerja Raya Malaysia (JKR, 2007) where excavation of large core-boulders (>0.5 m^3) is classified as hard material/rock excavation, and excavation of smaller core-boulders, and any material, other than hard material/rock, considered as common (soil) excavation.

During field mapping, colors (based on Munsell Soil Color Charts), particle sizes and textures of the exposed earth materials were identified and recorded, as were several morphological features considered to reflect differences in the extent of alteration of the orthopyroxene rhyodacite bedrock material and mass. Several weathering zones and sub-zones were then differentiated within the profile based on lateral similarity in earth materials and morphological features.

A schematic sketch was then prepared to show the distribution of morphological features within the profile, as well as the field differentiated weathering zones and sub-zones. Brass rings were then used to collect constant volume samples at various points along the slope cut (Figure 3) to allow for laboratory tests and more quantitative analyses of the exposed earth materials. Details on the method of sampling, as well as the various laboratory tests that were carried out, have been discussed in earlier publications (Raj, 2018; Raj, 2023). The earth materials in the different weathering zones and sub-zones were then characterized in

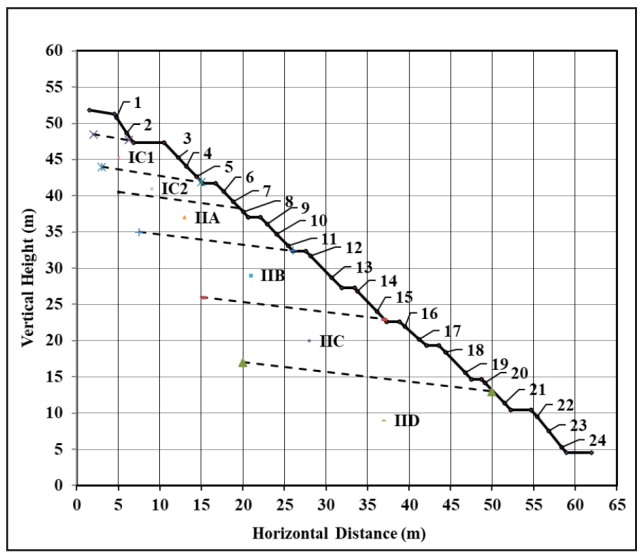


Figure 3: Sample locations and distribution of weathering sub-zones.

quantitative terms based on the laboratory tests. Rock mass weathering grades, based on IAEG (1981), ISRM (1981) and GSL (1990) were then assigned to the weathering profile, and this followed by the assignment of the rock mass classes of ISRM (2007) and ISRM (2015). The three schemes of characterization were then compared and their applicability discussed.

It is to be noted that the adopted method of field mapping and differentiation of weathering zones and sub-zones is similar to the procedure of several other workers from as long ago as Little (1969) and Deere & Patton (1971) to more recent workers as Lan *et al*. (2003), Rahardjo *et al*. (2004), Alavi *et al*. (2016), Jaques *et al*. (2021), Bonnet *et al*. (2022) and Bonnet *et al*. (2023). Alavi *et al*. (2016) furthermore, have stated that weathering profiles need to be characterized by field-scale observations and geological study, and proposed a typical weathering profile over granite in Johore State, based on geological and structural parameters.

Weathering zones and sub-zones

Field mapping of colors, textures and particle sizes of the exposed earth materials as well as morphological features (Table 1) allowed recognition of two broad zones and several sub-zones (or layers) at the weathering profile (Table 2). The two broad weathering zones are the upper, 12.2 m thick zone I of sandy clays with an absence of, or indistinct, relict bedrock textures, and the lower, >32.2 m thick zone II of sandy silts with distinct relict bedrock textures and structures and a few core-boulders (Table 2 and Figure 4). The upper zone I represents the pedological soil of the pedo-weathering profile concept, whilst the lower zone II represents the saprock (Tandarich *et al*., 2002; Graham *et al*., 2010).

Pedological features, including color (based on Munsell Soil Color Charts), consistency, soil structure and organic matter content allowed recognition of A, B and C soil horizons within zone I (Table 2). Soil horizons A and B consist of brown, soft to firm, sandy clay and constitute a 3.7 m thick solum, whilst the 8.5 m thick C horizon (saprolite) consists of brown to red, stiff sandy clays with indistinct relict bedrock texture that represent completely weathered orthopyroxene rhyodacite bedrock material. Absence, or presence, of indistinct relict quartz veins furthermore, allow the C horizon to be separated into upper (IC_1), and lower (IC_2), sub-zones, respectively (Table 2). Relict quartz veins are distinctly seen preserved at all levels within the saprock and indicate in situ development of the weathering profile (Figure 4).

Zone II (saprock) consists of yellowish red and yellowish brown to yellowish, bands of friable, silty sands that are considered to represent very highly to highly and moderately weathered, orthopyroxene rhyodacite bedrock

Table 1: Terminology for morphological features.

Term/Feature	Description
Distinct relict bedrock texture	Similar arrangement of mineral grains (both fresh and altered) in original, and in weathered, fine grained, acidic igneous bedrock.
Indistinct relict bedrock texture	Fairly similar arrangement of mineral grains (both fresh and altered) in original, and in weathered, fine grained, acidic igneous bedrock.
Distinct relict quartz vein	Quartz vein distinctly seen preserved in weathered bedrock (soil).
Indistinct relict quartz vein	Quartz vein indistinctly seen preserved in weathered bedrock (soil).
Distinct relict joint plane	Joint plane distinctly seen preserved in weathered bedrock (soil) with surface trace length >0.3 m.
Indistinct relict joint plane	Joint plane indistinctly seen preserved in weathered bedrock (soil) with surface trace length <0.3 m.
Distinct relict banding plane	Banding plane distinctly seen preserved in weathered bedrock (soil) with surface trace length >1.0 m.
Indistinct relict banding plane	Banding plane indistinctly seen preserved in weathered bedrock (soil) with surface trace length <1.0 m.
Distinct relict fault plane	Fault plane distinctly seen preserved in weathered bedrock (soil) with surface trace length >2.0 m (persistent).
Indistinct relict fault plane	Fault plane indistinctly seen preserved in weathered bedrock (soil) with surface trace length >1.0 m (discontinuous).

material. Variations in preservation of original bedrock structures and content of core-boulders allow zone II to be separated into 4 four sub-zones (Table 2 and Figure 4).

Large core-boulders are only found in the lower levels of saprock where they allow distinction of two sub-zones, i.e. the lowest sub-zone IID with core-boulders occupying >40% by area, and the overlying sub-zone IIC with core-boulders occupying <20% by area (Table 2 and Figure 4). These core-boulders have concentric weathering rims and are surrounded by yellowish silty sands with distinct relict bedrock texture representing moderately weathered bedrock material.

Indistinct relict joint planes, marked by short, surface trace lengths (<0.3 m) are seen in the upper levels of zone II, i.e., the 9.4 m thick sub-zone IIA where yellowish red, silty sands with distinct relict bedrock texture represent very highly weathered bedrock material. Distinct relict joint planes, marked by long surface trace lengths (>0.3 m), however, are seen in sub-zones IIB (9.4 m thick), IIC (9.8 m thick) and IID (>6.8 m thick) where yellowish brown, and yellowish, silty sands with distinct relict bedrock texture represent highly, and moderately, weathered bedrock material, respectively (Table 2 and Figure 4).

Indistinct relict banding planes, marked by discontinuous, relatively short, surface trace lengths (<1.0 m) furthermore, are seen in sub-zone IIA, whilst distinct relict banding planes, marked by long surface trace lengths (>1.0 m), are seen in sub-zones IIB, IIC and IID (Table 2 and Figure 4).

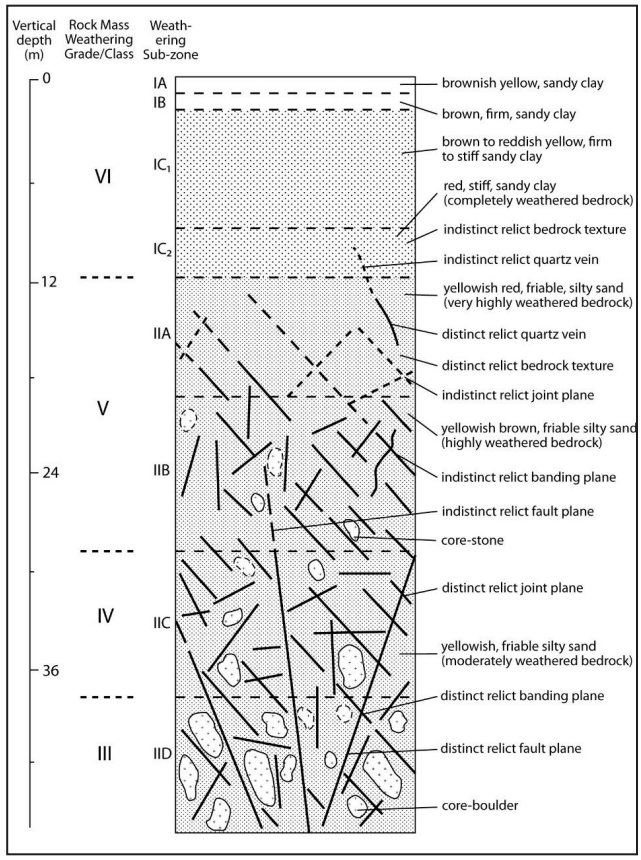


Figure 4: Schematic sketch of morphological features within the weathering profile.

Table 2: Morphological features of weathering sub-zones.

Sub-zone	Vertical depth (m)	Morphological features
IA	0.0-0.8	Brownish yellow (10YR6/8), soft, porous, sandy clay. Sub-angular blocky, moist. Many roots and burrows. Boundary irregular, diffuse.
IB	0.8-3.7	Brown (7.5YR5/8), firm, porous, sandy clay. Sub-angular blocky, moist. Some roots. Boundary irregular, diffuse.
IC_1	3.7-9.1	Brown (7.5YR5/8) to reddish yellow (7.5YR6/8), firm to stiff, sandy clay. Sub-angular blocky, moist. Boundary irregular, diffuse.
IC_2	9.1-12.2	Red (2.5YR4/8), stiff sandy clay with some yellow streaks and mottles. Sub-angular blocky, moist. Indistinct relict bedrock texture and quartz veins. Boundary irregular, diffuse.
IIA	12.2-18.4	Yellowish red, friable, silty sand. Distinct relict bedrock texture and quartz veins. A few indistinct relict joint and banding planes. Some thin bands of red, sandy clay. Boundary irregular, diffuse.
IIB	18.4-27.8	Yellowish brown, friable, silty sand. Distinct relict bedrock texture, quartz veins, joint and banding planes. Some indistinct relict fault planes. Some core-stones. Boundary, irregular, diffuse.
IIC	27.8-37.6	Yellowish brown and yellowish, bands of friable, silty sand. Distinct relict bedrock texture, quartz veins, joint, banding and fault planes. Some core-boulders with weathered rims (<20% by area). Boundary irregular.
IID	37.6-44.4	Yellowish and yellowish brown, bands of friable, silty sand with distinct relict bedrock texture, quartz veins, joint, banding and fault planes. Many core-boulders with weathered rims (>40% by area).

Note: Colors based on Munsell Soil Color Charts

Indistinct relict fault planes, marked by discontinuous, relatively long, surface trace lengths (>1.0 m) are seen in sub-zone IIB where yellowish brown, silty sands with distinct relict bedrock texture represent highly weathered bedrock material. Distinct relict fault planes with long surface trace lengths (>2.0 m) are seen in sub-zones IIC and IID where yellowish brown and yellowish, silty sands with distinct relict bedrock texture represent highly, and moderately, weathered bedrock material, respectively (Table 2 and Figure 4).

It is to be noted that distinct preservation of original bedrock textures and structures within saprock (zone II) is indicative of constant volume effects during weathering; a feature pointed out by Ollier (1969). Increased-volume weathering effects (i.e. the formation of larger volume, lower density weathering products) in pedological soil (zone I), however, lead to obliteration of the original bedrock textures and structures (Ollier, 1969; Thomas, 1974).

For reference purposes, it is to be noted that weathering profiles in China, are usually separated into five main zones, i.e. completely weathered, highly weathered, moderately weathered, lightly weathered, and fresh, rock (Lan *et al*., 2003). Field observations furthermore, allowed Alavi *et al*. (2016) to propose a typical weathering profile over granite where six broad zones (with four sub-zones) were differentiated, ranging from fresh, through slightly to moderately, highly, and completely, weathered bedrock to residual soil.

RESULTS

Variations in physical properties

The constant volume samples show physical properties of the earth materials to vary with depth, reflecting not only the extent of weathering of bedrock material, but also demarcating more clearly the field differentiated weathering zones and sub-sones. The red, stiff, sandy clay with indistinct relict bedrock texture of sub--zone IC_2 for instance, is characterized by an average dry unit weight of 15.44 kN/m^3, an average dry density of 1574 kg/m^3 and an average porosity of 39% (Table 3). The yellowish red, friable, silty

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

Sample	Depth (m)	Sub-zone	Dry Unit Weight (kN/m^3)	Dry Density (kg/m^3)	Specific Gravity Particles	Porosity (%)	Void Ratio	Water Content (%)	Degree Saturation (%)
1	0.5	IA	12.16	1240	2.59	52	1.09	30.0	71
2	2.6	IB	11.90	1213	2.58	53	1.13	32.0	73
3	6.1	IC_1	13.38	1364	2.57	47	0.88	27.0	79
4	7.2	IC_1	14.00	1427	2.58	45	0.81	27.0	86
5	8.6	IC_1	13.61	1387	2.59	46	0.87	26.7	80
6	10.7	IC_2	15.44	1574	2.59	39	0.65	21.0	84
7	12.1	IC_2	15.44	1574	2.58	39	0.64	20.0	81
8	13.5	IIA	14.77	1506	2.57	41	0.71	24.0	87
9	15.2	IIA	14.93	1522	2.59	41	0.70	23.4	86
10	16.6	IIA	14.06	1433	2.60	45	0.81	23.4	75
11	18.2	IIA	14.74	1503	2.58	42	0.72	25.0	90
12	19.6	IIB	13.17	1342	2.59	48	0.93	26.0	72
13	22.6	IIB	13.59	1385	2.60	47	0.88	23.0	68
14	24.5	IIB	13.07	1332	2.59	49	0.94	21.0	58
15	27.3	IIB	13.01	1326	2.60	49	0.96	20.1	54
16	29.4	IIC	12.77	1302	2.59	50	0.99	23.0	60
17	31.1	IIC	13.92	1419	2.60	45	0.83	20.4	64
18	32.9	IIC	11.88	1211	2.58	53	1.13	23.4	53
19	35.7	IIC	12.08	1231	2.61	53	1.12	25.0	58
20	37.1	IIC	11.96	1219	2.62	53	1.15	25.3	58
21	38.9	IID	13.66	1392	2.57	46	0.85	22.5	69
22	41.8	IID	13.37	1363	2.60	48	0.91	20.0	57
23	43.8	IID	13.51	1377	2.58	47	0.87	18.0	53
24	46.0	IID	13.12	1337	2.59	48	0.94	20.0	55

sand having distinct relict bedrock texture in sub-zone IIA furthermore, is characterized by an average porosity of 42%, and average dry unit weight of 14.63 kN/m^3 (Table 3).

The friable, yellowish brown, silty sand with distinct relict bedrock texture in sub-zones IIB and IIC represents highly weathered bedrock material, and is characterized by an average porosity of 48% and average dry unit weight of 13.21 kN/m^3 (Table 3). The friable, yellowish, silty sand having distinct relict bedrock texture in sub-zones IIC and IID represents moderately weathered bedrock material and is characterized by an average porosity of 47%, and an average dry unit weight of 13.42 kN/m^3 (Table 3).

Soil particles within the weathering profile have a limited range in values of specific gravity (SG) from 2.57 to 2.62 (Table 3), though this is not unexpected given the somewhat similar SG values of the primary (bedrock) and secondary (weathered) minerals present (Raj, 2018; Raj, 2023). Field moisture contents are variable with depth; the pedological soil with larger contents (>26.7%) than those of saprock (<25%) (Table 3). The degree of saturation reflects the values of moisture content with the pedological soil having higher values (>71%) than those of saprock (53-90%) (Table 3).

It is to be noted that closely similar variations in physical properties of earth materials with depth have also been seen in weathering profiles over porphyritic biotite granite (Raj, 1985), rhyolite (Raj, 2018) and sheared, biotite-muscovite granite (Raj, 2023).

Variations in soil index properties

The earth materials furthermore, show a distinct variation with depth of soil index properties; a variation that allows for a clearer demarcation of the field differentiated weathering zones and sub-zones (Table 4). Particle size distributions in the pedological soil (zone I) for instance, are characterized by large clay fractions (>27%), whereas those of saprock (zone II) are characterized by large silt fractions (>26%) (Table 4).

Table 4: Soil index properties of earth materials in the weathering profile.

Sample	Depth (m)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Plastic Limit (%)	Liquid Limit (%)	Textural Weathering Index (I_w)
1	0.5	0	24	13	63	34.0	66.0	0.83
2	2.6	0	23	14	63	36.0	77.8	0.82
3	6.1	0	28	17	55	34.5	80.5	0.75
4	7.2	0	30	19	51	34.0	68.0	0.73
5	8.6	0	33	18	49	34.1	75.7	0.73
6	10.7	7	39	19	35	31.7	61.0	0.65
7	12.1	2	45	26	27	30.5	54.7	0.51
8	13.5	4	39	38	19	31.9	48.0	0.33
9	15.2	2	38	38	22	29.6	46.3	0.37
10	16.6	3	42	34	21	30.2	49.0	0.38
11	18.2	7	45	29	19	30.7	50.5	0.40
12	19.6	4	36	36	24	36.0	54.0	0.40
13	22.6	4	37	33	26	30.9	49.0	0.44
14	24.5	2	42	42	14	36.9	49.0	0.25
15	27.3	3	42	45	10	39.0	Ind	0.18
16	29.4	9	60	26	5	33.9	Ind	0.16
17	31.1	9	59	26	6	37.7	Ind	0.19
18	32.9	2	46	40	12	40.3	Ind	0.23
19	35.7	2	56	38	4	36.2	Ind	0.10
20	37.1	4	55	40	1	37.5	Ind	0.02
21	38.9	2	54	42	2	34.8	Ind	0.05
22	41.8	3	51	44	2	35.8	Ind	0.04
23	43.8	3	56	40	1	36.1	ind	0.02
24	46.0	8	53	39	0	33.6	ind	0.00

Note: ind means indeterminate

The red, stiff, sandy clay of sub-zone IC_2 which represents completely weathered bedrock material, is characterized by average gravel, sand, silt and clay contents of 5%, 42%, 23% and 30%, respectively, and plastic and liquid limits of 31.1%, and 57.9% (Table 4). The friable, yellowish red, silty sand of sub-zone IIA, represents very highly weathered bedrock material and is characterized by average gravel, sand, silt and clay contents of 4%, 41%, 35% and 20%, respectively, and average plastic and liquid limits of 30.6%, and 48.5% (Table 4). The friable, yellowish brown, silty sand of sub-zones IIB and IIC furthermore, is characterized by average gravel, sand, silt and clay contents of 3%, 39%, 39% and 19%, respectively and plastic and liquid limits of 35.7%, and 50.7% (Table 4). The friable, yellowish, silty sand of sub-zones IIC and IID represents moderately weathered bedrock material, and is characterized by average gravel, sand, silt and clay contents of 5%, 55%, 34% and 6%, respectively with a plastic limit of 37.1%, and an indeterminate liquid limit (Table 4).

It is to be noted that these variations with depth of soil index properties are closely similar to those reported for the earth materials of weathering profiles over other acidic igneous bedrock, including porphyritic biotite granite (Raj, 1985), rhyolite (Raj, 2018) and sheared, biotite-muscovite granite (Raj, 2023). Differences in textures of the original bedrock material and mass, however, do result in some variations of soil index properties.

Variations in mineral composition

Binocular microscope observations of the silt, sand, and gravel, fractions of samples after sieving show some differences in mineral composition that reflect increasing effects of weathering and pedological processes up the profile. Silt fractions of all samples consist entirely of sericite flakes, whilst quartz grains are the predominant component of sand and gravel fractions. The quartz grains are fine grained and stained pink to red in samples from the pedological soil (zone I), but are coarser grained and cloudy to clear with vitreous lustres in samples from saprock (zone II). Some kaolinized (white) and unaltered (cloudy) feldspar grains are seen in the sand fractions of the saprock sub-zones IIC and IID, but are not seen in sub-zones higher up the profile. Decreasing sand (and gravel) contents up the profile point to the continued upward disintegration (or disaggregation) of quartz grains, whilst decreasing silt, but increasing clay, contents up the profile (Table 3) indicate their continued upward disintegration.

X-ray diffractograms (XRD) show high background values with low reflection peaks that point to the limited clay fractions present, especially those from saprock (Figure 5). Kaolinite is the only clay mineral of the pedological soil horizons IA and IC together with some gibbsite and goethite occurring as non-phyllosilicates. Kaolinite is also the only clay mineral of the upper saprock sub-zone IIA, whilst both kaolinite and meta-halloysite are present in

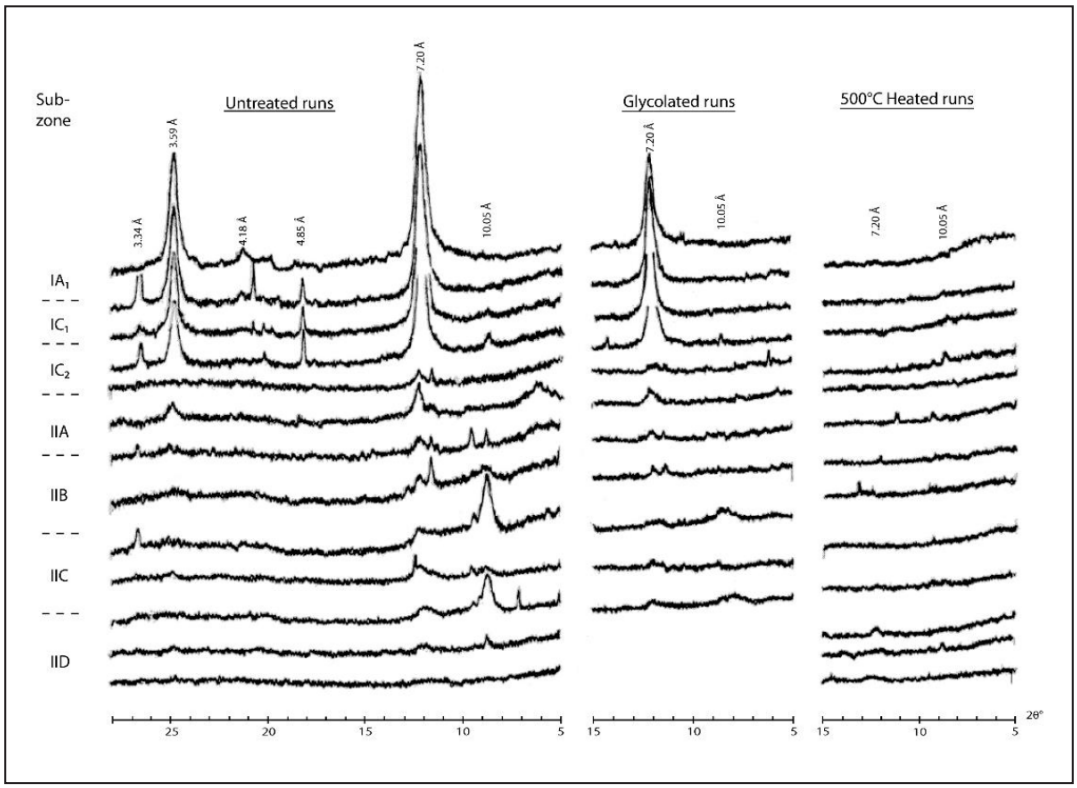


Figure 5: X-ray diffractograms of clay fractions in the weathering profile.

sub-zone IIB. In the bottom sub-zones IIC and IID, meta-halloysite is the predominant clay mineral with kaolinite occurring in smaller amounts (Figure 5). Identification of the clay minerals (kaolinite and meta-halloysite) as well as non-phyllosilicates (gibbsite and goethite), is based on the shapes of the main reflection peaks and their changes on the three diffractograms determined under different conditions (Figure 5) (Thorez, 1975).

Variations in textural weathering index (I_w)

Raj (2018) proposed the textural weathering index [I_w = (Clay Content) / (Clay + Silt Contents)] to illustrate the extent of weathering of bedrock material within a weathering profile over rhyolite. Application of this weathering index (I_w) to the present profile is most illustrative for differences in clay and silt contents result in the pedological soil (zone I) being characterized by larger indices (I_w>0.5) than those of saprock (zone II) (I_w<0.4) (Table 4). Sub-zones IIA and IIB furthermore, have average textural weathering indices of 0.37, and 0.32, respectively, while sub-zones IIC and IID have average values of 0.14, and 0.03, respectively.

As in the case of the weathering profile over rhyolite (Raj, 2018), there is a gradual increase in the weathering index upwards within saprock; an increase that reflects increasing clay contents (of kaolinite and meta-halloysite) that coincide with decreasing silt contents (of sericite). Increasing clay contents therefore, are considered to reflect increasing disintegration and decomposition of silt sized particles of mostly sericite that result from decomposition of feldspars in the original bedrock material. Inherent differences in texture and composition within the orthopyroxene rhyodacite bedrock material, however, do result in some minor variations of the weathering index.

Assigning grades to the weathering profile

The assignment of rock mass weathering grades to weathering profiles is based on the premise that the profiles have resulted from weathering of rock masses, and can therefore, be described in terms of "the distribution and relative proportions of fresh rock, discolored, decomposed and disintegrated rock, and effects on discontinuities" (IAEG, 1981; ISRM, 1981). Several schemes have been proposed for the assignment of rock mass weathering grades; the more well-known ones being the IAEG (1981), ISRM (1981) and GSL (1990) schemes.

Six weathering grades have been defined; grade I being "a fresh rock mass with no visible sign of rock material weathering", and grade VI being "a residual soil where all rock material has been converted to soil with destruction of the mass structure and material fabric and a large change in volume (though the soil has not been significantly transported)" (IAEG, 1981). Grade II is considered to be "a slightly weathered rock mass where discoloration indicates weathering of rock material and discontinuity surfaces", whilst Grade III is "a moderately weathered rock mass where <35% of the rock material is decomposed and/or disintegrated to a soil with fresh or discolored rock present as a discontinuous framework or as core-stones" (ISRM, 1981). Grade IV refers to "a highly weathered rock mass where >35% of the rock material is decomposed and/or disintegrated to a soil and fresh rock present as a discontinuous framework or as core-stones" (IAEG, 1981). Grade V refers to "an extremely weathered rock mass where all rock material is decomposed and/or disintegrated to a soil, though the original mass structure is still present" (IAEG, 1981; ISRM, 1981).

Assigning grades to the present weathering profile is straight-forward with the pedological soil (zone I) being directly correlated with grade VI (residual soil) as all rock material has been "converted to soil with destruction of the mass structure and material fabric and a large change in volume though the soil has not been significantly transported" (Figure 4). Weathering sub-zone IID furthermore, can be correlated with grade III (moderately weathered) for "<35% of its rock material is decomposed and/or disintegrated to a soil"; there being >40% by area of fresh or discolored rock present as core-boulders (Figure 4). Weathering sub-zone IIC can be correlated with grade IV (highly weathered) for ">35% of its rock material is decomposed and/or disintegrated to a soil"; there being <20% by area of fresh or discolored rock present as core-boulders (Figure 4). Weathering sub-zones IIA and IIB finally can be correlated with grade V (extremely weathered) for all "rock material is decomposed and/or disintegrated to soil with the original mass structure (or texture) still largely intact" (Figure 4).

The distinctive feature in geotechnical characterization of the weathering profile through the assignment of rock mass weathering grades is that the characterization essentially involves rock material properties, and does not take into consideration the many, indistinctly to distinctly preserved, relict geological structures present, including joint, banding and fault planes (Figure 4).

Assigning rock mass classes to the weathering profile

Recognition of different rock mass classes in the ISRM (2007) and ISRM (2015) suggestions for classification and description of rock masses is based on the assignment of weathering grades to weathering profiles as stated in the original proposal of ISRM (1981). In this original proposal, grades were assigned to weathering profiles as they (the profiles) were considered to result from weathering of rock masses, and could therefore, be described in terms of "the distribution and relative proportions of fresh rock, discolored, decomposed and disintegrated rock, and effects on discontinuities" (ISRM, 1981).

Six rock mass classes have been defined; class I being "a sound rock mass with no visible sign of matrix weathering though some discoloration may be present along the main

discontinuities" (ISRM, 2015). Class II is considered to be "a slightly weathered rock mass where discoloration indicates the start of rock matrix weathering and along discontinuity planes" (ISRM, 2007). Class III refers to "a moderately weathered rock mass where <50% of the rock material is decomposed or disintegrated to a soil condition with sound or discolored rock present as discontinuous zones or as core-stones" (ISRM, 2015). Class IV refers to "a highly weathered rock mass where >50% of the rock matrix is decomposed or disintegrated to a soil condition with sound or discolored rock present as discontinuous zones or as core-stones" (ISRM, 2007). Class V refers to "a completely weathered rock mass where all rock matrix is decomposed or disintegrated to a soil condition with the original structure of the rock mass commonly preserved", and class VI is "a residual soil where all rock has been transformed into a soil with great volume variation, though no significant soil transport" (ISRM, 2007; ISRM, 2015).

Assigning rock mass classes to the present weathering profile is straight-forward with the pedological soil (zone I) being directly correlated with class VI (residual soil) as all "rock has been transformed into soil with great volume variation but no significant soil transport" (Figure 4). Weathering sub-zones IIA and IIB can then be correlated with rock mass class V (completely weathered) for "all rock matrix is decomposed or disintegrated to a soil condition with the original structure commonly preserved" (Figure 4). Weathering sub-zone IIC can be correlated with class IV (highly weathered) for ">50% of its rock matrix is decomposed or disintegrated to a soil condition"; there being <20% by area of sound or discolored rock present as core-boulders (Figure 4). Weathering sub-zone IID can be correlated with class III (moderately weathered) as "<50% of its rock matrix is decomposed or disintegrated to a soil condition"; there being >40% by area of sound or discolored rock present as core-boulders (Figure 4).

As with the assignment of rock mass weathering grades, the distinctive feature in geotechnical characterization of the weathering profile through assignment of rock mass classes is that the classification is essentially based on rock material properties, and does not take into account the many, indistinctly to distinctly preserved, relict geological structures (Figure 4).

DISCUSSION

In situ development of weathering profile

Indistinctly to distinctly preserved minerals, textures and structures of the original orthopyroxene rhyodacite bedrock material and mass clearly indicate in situ development of the weathering profile. Recognition of the pedological soil, and saprock, zones furthermore, supports the contention of Carroll (1970) that "chemical weathering in the upper levels of the lithosphere involves two stages; the first involving the production of rotten rocks, on which the second (soil formation) takes place". The pedological soil can thus be considered to result from alteration of bedrock by both geochemical and pedological processes, whilst the saprock results from alteration of bedrock by geochemical processes (Carroll, 1970; Jaques *et al*., 2021). Differentiation of the pedological soil and saprock zones also allows application of the "pedo-weathering profile concept; a synthetic paradigm that melds pedological and geological profile concepts" (Tandarich *et al*., 2002).

Preservation of bedrock structures

A significant feature of the field differentiated weathering zones and sub-zones is recognition and mapping of the indistinctly to distinctly preserved, relict bedrock structures (Figure 4). These relict structures, i.e., joint, banding and fault planes, are found at different levels within the weathering profile and have influenced in part, the development of the various sub-zones through their control on the movement of groundwater (Figure 4).

Recognition and mapping of relict bedrock structures cannot be over-emphasized in view of the many published papers describing their (the structures) impact and influence on the stability of slope cuts in the residual soils of humid tropical areas as St. John *et al*. (1969), Deere & Patton (1971), Aydin *et al*. (2000), Aydin & Wen (2003), Aydin (2006), Wesley (2009) and Wesley (2011). Relict structures and textures as well as particles of variable composition and size in residual soils furthermore, are absent in transported soils which are strongly influenced by their stress history (Tan & Gue, 2001). Slope designs that are both safe and economic for open-pit mines in tropical and sub-tropical residual soils also require special understanding of their behavior and characteristics, in particular the presence of relict structures and their relatively low strength (Mandisodza & Dunn, 2019). The need for recognition of relict geological structures or "structural prominence" has also been emphasized in a recent study of weathering profiles over andesite from the Dullstroom Formation of South Africa for the relict structures (whose preservation decreases with increasing weathering) influence the compressibility and porosity of the weathered bedrock materials (Swart & Dippenaar, 2025).

Weathering zones and sub-zones in comparison with rock mass weathering grades and rock mass classes

The most significant difference between the field differentiated weathering zones and sub-zones, and the assigned rock mass weathering grades and rock mass classes is in the implicit recognition and mapping of relict bedrock structures, i.e., joint, banding and fault planes. The assignment of rock mass weathering grades is essentially based on rock material properties, and does not take into account the many, indistinctly to distinctly preserved, relict bedrock structures present (Figure 4). Discontinuity planes are only implicitly considered in assigning rock mass weathering grades I and II; grade I being "fresh rock with no

visible sign of rock material weathering though there maybe some discoloration on major discontinuity surfaces", and grade II being "slightly weathered rock with discoloration indicating weathering of rock material and discontinuity surfaces" (IAEG, 1981; ISRM, 1981). Discontinuity planes, however, are not implicitly considered in assigning rock mass weathering grades III, IV, V and VI; a limitation that can be improved by including morphological criteria when these grades are assigned to weathering profiles. Rock mass weathering grade III can therefore, be considered to represent moderately weathered bedrock with distinct relict joint, banding, and fault, planes, whilst grade IV can be considered to represent highly weathered bedrock with distinct banding and joint planes, and grade V considered to represent very highly weathered bedrock with indistinct relict joint and banding planes.

The assignment of rock mass classes is also essentially based on rock material properties, and does not take into consideration the many, indistinctly to distinctly preserved, relict geological structures present (Figure 4). Discontinuity planes are only implicitly considered in assigning rock mass classes I and II; rock mass class I being "a sound rock mass with no visible sign of matrix weathering, though there maybe some discoloration along main discontinuities", and class II being "a slightly weathered rock mass with discoloration of rock indicating the beginning of rock matric weathering and along discontinuity surfaces" (ISRM, 2007; ISRM, 2015). Discontinuity planes are not implicitly considered in assigning rock mass classes III, IV, V and VI; a limitation that can be improved by including morphological criteria when these classes are assigned to weathering profiles. Rock mass class III can therefore, be considered to represent a moderately weathered bedrock mass with distinct relict joint, banding, and fault, planes, whilst class IV can be considered to represent a highly weathered bedrock mass with distinct banding and joint planes, and class V considered to represent a very highly weathered bedrock mass with indistinct relict joint and banding planes.

CONCLUSION

1. Field mapping of morphological features allowed differentiation of two broad weathering zones, i.e. an upper, 12.2 m thick, zone I (pedological soil) of sandy clays with indistinct relict bedrock textures, and a lower, >32.2 m thick, zone II (saprock) of silty sands with distinct relict bedrock textures and structures and some core-boulders.

2. Soil horizons A, B and C constitute the pedological soil (zone I), whilst the saprock (zone II) can be separated into sub-zones IIA, IIB, IIC and IID based on differences in preservation of bedrock joint, banding and fault planes as well as content of core-boulders.

3. Stiff, red, sandy clay with indistinct relict bedrock texture in sub-zone IC represents completely weathered bedrock material having an average dry unit weight of 15.44 kN/m^3 and porosity of 39%, and consists of 5% gravel, 42% sand, 23% silt and 30% clay fractions, with plastic and liquid limits of 31.1%, and 57.9%, respectively.

4. Friable, yellowish red, silty sand with distinct relict bedrock texture in sub-zone IIA represents very highly weathered bedrock material having an average dry unit weight of 14.63 kN/m^3 and porosity of 42% and consists of 4% gravel, 41% sand, 35% silt and 20% clay fractions with plastic and liquid limits of 30.6%, and 48.5%, respectively.

5. Friable, yellowish brown, silty sand with distinct relict bedrock texture in sub-zones IIB and IIC represents highly weathered bedrock material having an average dry unit weight of 13.21 kN/m^3 and porosity of 48% and consists of 3% gravel, 39% sand, 39% silt and 19% clay fractions with plastic and liquid limits of 35.7%, and 50.7%, respectively.

6. Friable, yellowish, silty sand with distinct relict bedrock texture in sub-zones IIC and IID represents moderately weathered bedrock material having an average dry unit weight of 13.42 kN/m^3 and porosity of 47% and consists of 5% gravel, 55% sand, 34% silt and 6 % clay fractions with a plastic limit of 37.1%, but indeterminate liquid limit.

7. Relict joint and banding planes are indistinctly preserved in sub-zone IIA, but are distinctly preserved in sub-zones IIB, IIC and IID where indistinct to distinct relict fault planes are also present.

8. Core-boulders constitute <20%, and >40%, by area of sub-zones IIC and IID, respectively; these sub-zones also characterized by distinctly preserved relict banding, joint and fault planes.

9. Decreasing sand contents up the profile indicate increasing, upward disintegration of quartz grains, whilst increasing clay, and decreasing silt, contents indicate upward disintegration of silt particles.

10. Indistinct to distinct preservation of original bedrock minerals, textures and structures indicate that the weathering profile has resulted from in situ alteration (disintegration and decomposition) of an orthopyroxene rhyodacite bedrock mass.

11. The pedological soil (weathering zone I) can be equated with weathering grade VI, or class VI, of standard rock mass weathering classification schemes, whilst sub-zone IID is correlated with grade, or class, III, sub-zone IIC correlated with grade or class IV, and sub-zones IIA and IIB correlated with grade or class V.

12. It is recommended that morphological criteria, i.e. the recognition of relict bedrock structures, be included in the descriptions for recognition of rock mass weathering grades, and rock mass classes.

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CONFLICT OF INTEREST

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

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