Bulletin of the Geological Society of Malaysia, Volume 76, November 2023, pp. 55 - 62
DOI: https://doi.org/10.7186/bgsm76202305

Rock - soil transition during weathering of rhyolite

John Kuna Raj

No. 83, Jalan Burhanuddin Helmi 2, Taman Tun Dr. Ismail, 60000 Kuala Lumpur, Malaysia
Email address: jkr.ttdi.tmc@gmail.com

Abstract: Concentric layers of weathered materials around core-stones show the rhyolite to experience sequential, but gradational, changes in visible features, textures and mineralogy as it transforms from 'rock' into 'soil'. The changes start with the opening-up of grain boundaries and micro-cracks (stage 1) followed by their dark brown staining (stage 2) and the subsequent alteration (to sericite and clay minerals) of plagioclase feldspar groundmass grains and phenocrysts (stage 3). Biotite flakes are then bleached and altered (to chlorite and clay minerals) (stage 4) before there starts alteration (to sericite and clay minerals) of groundmass alkali feldspar grains (stage 5) and finally alteration of alkali feldspar phenocrysts (stage 6). Quartz grains are not altered during these stages of weathering but disaggregate and reduce in size due to continual opening-up of grain boundaries and micro-cracks. Increasing stages of weathering are marked by decreasing dry unit weights, dry densities and uniaxial compressive strengths, but increasing apparent porosities. The transition between 'rock' and 'soil' occurs during weathering stage 6 when all plagioclase groundmass grains and phenocrysts have been altered as have been all alkali feldspar groundmass grains and most phenocrysts. Stage 6 is marked by large apparent porosities (>14%) but low values of dry unit weight (<21.90 kN/m^3) and dry density (<2,232 kg/m^3).

Keywords: rhyolite, weathering, rock-soil transition, core-stones

INTRODUCTION

The changes in mineralogy and texture that occur when rocks are weathered have been investigated with the aid of several chemical and petrological methods as well as laboratory index tests or assessed indirectly in the field (Bell, 2000). Several indices have been derived to quantify the changes in purely geological properties; some of them applied to correlate with, and indirectly determine, the engineering properties of weathered rock (Irfan, 1996). Reviews of the various methods used to characterize the weathering of rock are discussed in Martin & Hencher (1986) as well as Irfan (1996) and Bell (2000).

Several workers have applied essentially physical criteria to characterize the weathering of rock as Melton (1965) who used staining and friability of rock fragments to identify the degree of chemical weathering, and Ollier (1965) who proposed a similar scale based on friability alone to describe the weathering of granite. Onodera *et al.* (1974) used the number and width of micro-cracks as an index of the physical weathering of granite, while Uriel & Dapena (1978) proposed a void index to quantify the degree of physical weathering of granite. Iliev (1966) proposed a coefficient of weathering for granitic rock based on ultrasonic velocities in fresh, and weathered rock, whilst Irfan & Dearman (1978a) proposed a micro-petrographic index based on the ratio of primary to secondary minerals, micro-cracks and voids, to assess the grade of weathering of granite. After an extensive testing program, Irfan & Dearman (1978b) concluded that the quick absorption, Schmidt hammer, and point load strength, tests were reliable field tests for determination of a quantitative weathering index for granite. The main limitation in the use of such physical criteria to define the degree of weathering is that they can only be applied to material that is still sufficiently cohesive to be regarded as rock (Thomas, 1974).

Chemical analyses and calculation of various elemental, compound or molecular ratios, have also been widely used to define the state of weathering of rock material. Irfan (1996) applied several of these indices in the assessment of weathered granites in Hong Kong and concluded that the silica-to-alumina ratio as well as the Parker index (Parker, 1970) and the mobiles index (Irfan, 1996) were good indicators of the degree of weathering. Duzgoren-Aydin *et al.* (2002), however, applied thirty different chemical indices of weathering in their study of a weathering profile over crystal-vitric tuff in Hong Kong and concluded that application of these indices to directly scale changes in the physical state of rock material may not be warranted due to the complications involved. Duzgoren-Aydin & Aydin (2006) in a comprehensive re-assessment of chemical weathering indices for felsic igneous rocks in Hong Kong furthermore, concluded that chemical weathering indices were not as useful in determining weathering grades as was originally thought, though they could be used as tools to detect chemical heterogeneities.

0126-6187; 2637-109X / Published by the Geological Society of Malaysia.

In weathering profiles over granite, different stages of weathering of rock material are often present at similar depths, as in the concentrically developed stages of weathering around core-stones and core-boulders (Dearman, 1974). Dearman (1976), and Lee & de Freitas (1989), have thus, emphasized the need to differentiate between "weathering of rock material" and "weathering of rock mass". Martin & Hencher (1986) have also pointed out that weathering profiles are characterized by heterogeneous earth materials at various stages of decomposition and/or disintegration as weathering processes are rarely sufficiently uniform to give gradual and predictable changes in mineralogical and textural properties.

Concentric rings of weathered material around core-stones have shown a porphyritic biotite granite to experience sequential, but gradational, changes in visible features, textures and mineralogy as it transforms from 'rock' into 'soil' (Raj, 2022). The changes start with the opening-up of grain boundaries and micro-cracks (stage 1) followed by their dark brown staining (stage 2) and the subsequent alteration of groundmass plagioclase feldspar grains (stage 3). Biotite flakes are then bleached and altered (stage 4) before there starts alteration of groundmass alkali feldspar grains (stage 5) and finally alteration of alkali feldspar phenocrysts (stage 6). Quartz grains are not altered during these stages of weathering, but disaggregate and reduce in size due to continual opening-up of grain boundaries and micro-cracks. Increasing stages of weathering are marked by decreasing dry unit weights, dry densities and uniaxial compressive strengths, but increasing apparent porosities. The transition between 'rock' and 'soil' occurs during weathering stage 6 when all plagioclase, and most alkali feldspar, groundmass grains have been altered as have been some alkali feldspar phenocrysts (Raj, 2022).

In an earlier publication, Raj (2018) has described the physical characterization of the weathering profile developed over rhyolite at km 38.2 of the Kuala Lumpur - Karak Highway. In this geological short-note, the concentric stages of weathering that develop around core-stones at the weathering profile are discussed in order to define more clearly the transition between 'rock' and 'soil' in weathering of the rhyolite.

METHODOLOGY

Several core-stones were first collected at the weathering profile over rhyolite at km 38.2 (east bound) of the Kuala Lumpur - Karak Highway (Figure 1). These litho-relicts were taken to the laboratory where they were diamond-sawn into slabs of variable thicknesses. The concentric rings of weathered materials around the rims of the slabs were then examined with a hand lens to identify differences in visible features as staining, colour, texture and appearance of mineral grains. The extent of alteration of feldspar phenocrysts and groundmass grains was also determined following the method of Irfan & Dearman (1978b) (Table 1). Thin-sections were then prepared of the concentric rings of weathered materials and a petrological microscope used to identify changes in texture and mineralogy of the phenocrysts and groundmass grains.

Variations in visible features as well as textural and mineralogical changes were then used to define different stages of weathering of the rhyolite core-stones. This procedure of identifying different stages of weathering follows that of earlier workers as Ruxton & Berry (1957) who defined stages of weathering of granitic rock material in terms of staining and alteration of mineral grains as well as the friability of material. Baynes *et al.* (1978), Irfan & Dearman (1978a) and Dearman *et al.* (1978) furthermore, have adopted a similar procedure to define different stages of weathering of granite in southwest England on the basis of separate assessments of the effects of physical disintegration and chemical decomposition.

Small tetrahedral blocks of the different stages of rhyolite weathering were also sawn-out from the slabs and their unit weights, densities and apparent porosities determined by the saturation and buoyancy method of ISRM (1979). Some of these tetrahedral blocks were also loaded

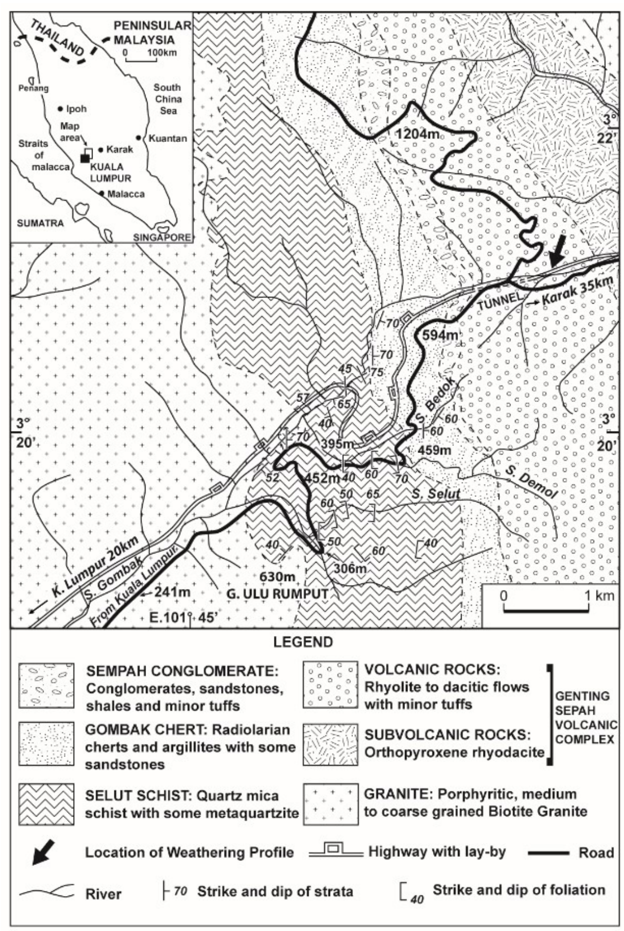

Figure 1: Geology map of the G. Ulu Rumput area (after Haile *et al.*, 1977; Azman & Singh, 2005).

Table 1: Extent of alteration of feldspar grain (after Irfan & Dearman, 1978b).
(Material from probed feldspar grain rubbed between thumb and finger).

Feel	Description	Interpretation
Gritty	Partially decomposed	Feldspar grain altered to sericite & clay along micro-fracture and cleavage planes only
Powdery (Silky)	Completely decomposed	Feldspar grain entirely altered to mainly sericite and some clay
Clayey	Completely decomposed	Feldspar grain entirely altered to clay and some sericite

to failure in a compression machine following standard procedure in order to determine uniaxial compressive strengths (ISRM, 1981).

GEOLOGICAL SETTING OF WEATHERING PROFILE

The rhyolite bedrock exposed at the cut slope at km 38.2 of the Kuala Lumpur - Karak Highway forms part of a broad, approximately north-south trending belt of acid volcanics within the Main Range of Peninsular Malaysia (Figure 1). The acid volcanics comprise rhyolitic to dacitic flows with minor tuffs and tuff breccias and are considered to be contemporaneous with the Sempah Conglomerate which outcrops to their immediate west (Haile *et al.*, 1977). Towards the east, however, the volcanics appear to be faulted against micro-granodiorite with an unusual mineralogy; consisting of abundant quartz, orthoclase, andesine and biotite together with orthopyroxene and labrodorite (Liew, 1977). Cobbing & Mallick (1987) consider this micro-granodiorite to be a subvolcanic rock that together with the acid volcanics constitutes their Genting Sempah Micro-granodiorite Pluton.

Chakraborty (1995), and Singh & Azman (2000), however, consider the acid volcanics (which they call ‘orthopyroxene lacking rhyodacitic rocks’ or ‘rhyodacite’) and the micro-granodiorite (which they call ‘orthopyroxene bearing rhyodacite porphry’ or ‘orthopyroxene rhyodacite’) to constitute their Genting Sempah Volcanic Complex. This Volcanic Complex is considered to comprise two distinctive porphyry sub-volcanic units, i.e., rhyolite, and orthopyroxene rhyodacite, with minor tuffs and lavas (Azman & Singh, 2005). The Genting Sempah Volcanic Complex is considered to be one of the few examples of acid volcanism that is related, both temporally and spatially to the Triassic Main Range Granite; radiometric dating (U-Pb zircon data) yielding an age range between 211 and 219 Ma (million years) (Liew & Page, 1985).

The bedrock at the foot of the slope cut is bluish-grey in color and occurs as a massive, apparently structureless outcrop, though aligned biotite flakes (striking north-south and dipping 40^{o} east) suggest magmatic flow. The bedrock is moderately to strongly jointed (with fracture spacings between 0.2 and 0.7 m) and often contains epidote along joint planes. In thin-sections, the rhyolite is seen to be hypidomorphic, holocrystalline with phenocrysts (some 40-60%) of quartz, plagioclase, biotite and alkali feldspar set in an aphanitic, essentially quartzo-feldspathic groundmass (Liew, 1977). The groundmass shows minor variations in grain size with that surrounding most phenocrysts being finer grained than that not associated with reaction rims (Azman & Singh, 2005).

Quartz occurs as large phenocrysts (2-4 mm) and as smaller (0.3-0.5 mm) rounded micro-phenocrysts and is an essential constituent of the groundmass. Most quartz grains are subhedral and exist as discrete crystals, though rare monomineralic clusters of quartz (2 mm) are also seen. Plagioclase occurs as individual euhedral to subhedral laths and as angular fragments of variable size with phenocrysts of 1 to 4 mm in size, and micro-phenocrysts from 0.5 to 0.7 mm. The plagioclase displays albite, Carlsbad-albite and pericline twinning as well as both oscillatory and normal zoning. Determination of anorthite percentage using extinction angles of albite twins show a compositional range from An_{30}-An_{42} (andesine) (Azman & Singh, 2005). Biotite occurs as euhedral to subhedral phenocrysts of up to 5 mm in diameter and is extremely rare as a groundmass constituent where it occurs as small shreds. Alkali feldspar (micro-perthite orthoclase) phenocrysts are often ornamented by internal zones and blebs of groundmass crystals, whilst micro-perthite, varying in size from 1 to 4 mm, typically displays embayment structures with various inclusions of accessory minerals (Azman & Singh, 2005).

RESULTS

Stages of weathering

Variations in visible features as well as textural and mineralogical changes allow differentiation of six generalized stages of weathering of the rhyolite (Tables 2 and 3). These stages of weathering, as illustrated in Figure 2, start with the opening-up of grain boundaries and micro-cracks (stage 1) followed by their dark brown staining with secondary iron oxides and hydroxides (stage 2). Plagioclase groundmass grains and phenocrysts then start to alter (to sericite and clay minerals) (stage 3) before there is bleaching and alteration (to chlorite and clay minerals) of biotite flakes (stage 4). There is then the alteration (to sericite and clay minerals) of the groundmass alkali feldspar grains (stage

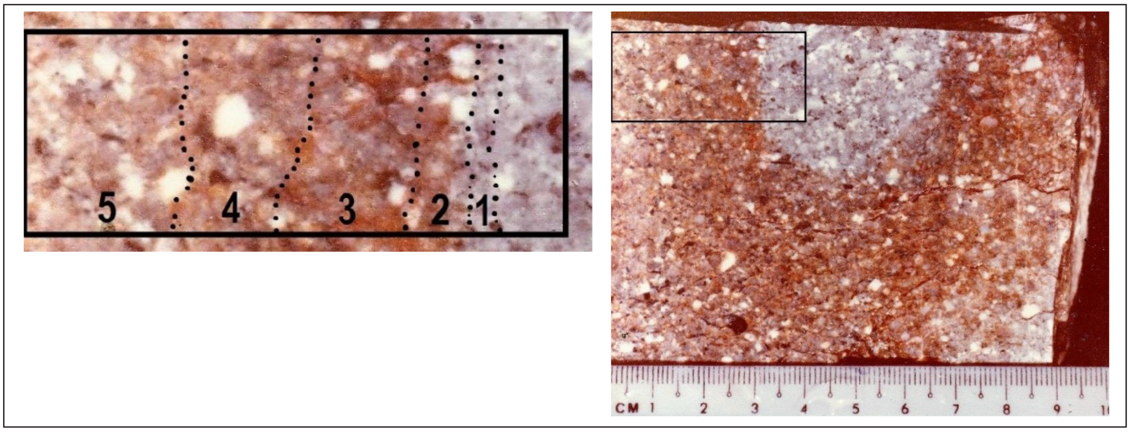

Figure 2: Weathering stages 1 to 5 around core-stone of rhyolite.

Table 2: Stages of weathering around rhyolite core-stones.

Stage	Hand specimen description	Thin-section description
6	Pink to yellow 'rock' material with brown stains along open grain boundaries and micro-cracks. Quartz grains unaltered while biotite flakes all altered (bleached). Most feldspar groundmass grains and phenocrysts altered - gritty to powdery (≈40% of all grains). 'Rock' material has weak fabric and can disaggregate when dry samples are agitated in water.	Quartz grains unaltered, though all plagioclase, and most alkali feldspar, groundmass grains & phenocrysts are altered (to sericite and clay minerals). Biotite flakes all altered (to chlorite and clay minerals). Grain boundaries and micro-cracks all open. Some yellow stains along grain boundaries.
5	Brownish grey rock material with brown stains along many open grain boundaries and micro-cracks. Stains prominent around biotite flakes (appear bleached). Quartz grains unaltered whilst many feldspar ground-mass grains and phenocrysts altered - gritty to powdery (≈20-30% of all grains).	Quartz grains unaltered, though all plagioclase and many alkali feldspar, groundmass grains and phenocrysts altered (to sericite and clay minerals). Brown stains, radiate away from altered biotite flakes (bleached). Brown stains along many grain boundaries and microcracks.
4	Brownish grey rock material with brown stains along grain boundaries and micro-cracks. Quartz grains unaltered with vitreous to sub-vitreous lustres. Many feldspar groundmass grains and phenocrysts altered - gritty (≈10-20% of all grains).	Quartz grains unaltered, whilst many plagioclase and some alkali feldspar, groundmass grains and phenocrysts altered (to sericite). Some biotite flakes bleached and altered (to chlorite). Brown stains along most grain boundaries and micro-cracks.
3	Dark brownish grey rock material with brown stains along grain boundaries and micro-cracks. Mineral grains mostly unaltered with vitreous to sub-vitreous lustres. Some feldspar groundmass grains are gritty (<10% of all grains).	Essential mineral grains mostly unaltered. Some plagioclase groundmass grains and phenocrysts altered (to sericite). Brown stains seen along most grain boundaries and micro-cracks.
2	Brownish grey rock material with brown stains along some grain boundaries. Essential mineral grains appear unaltered with vitreous to sub-vitreous lustres.	Essential mineral grains appear unaltered, though brown stains seen along some open grain boundaries and micro-cracks.
1	Bluish grey rock material. Phenocrysts and groundmass mineral grains appear unaltered with vitreous to sub-vitreous lustres. Some open grain boundaries and micro-cracks.	Essential mineral grains (quartz, biotite, alkali feldspar and plagioclase) appear unaltered. A few open grain boundaries and micro-cracks.
	Bluish grey rock material. Essential minerals (quartz, biotite, alkali feldspar and plagioclase), occurring as phenocrysts and groundmass grains, appear unaltered with vitreous to sub-vitreous lustres. Grain boundaries and micro-cracks are tight (closed).	Essential minerals (quartz, biotite, alkali feldspar and plagioclase) occurring as phenocrysts and groundmass grains appear unaltered. A few feldspar and quartz phenocrysts are fissured. Grain boundaries and micro-cracks are tight (closed).

Table 3: Variations in visible features and mineralogy during different stages of weathering.

Stage	Grain Boundaries & Micro-cracks	Primary (essential) Minerals				Altered Feldspar Grains (% of all grains)	Secondary	
		Phenocrysts & Groundmass						
		Quartz	Alkali Feldspar	Plagio-clase	Biotite		Silt size (Sericite)	Clay size
6	Most open with yellow stains	Unaltered	Most altered	All altered	All altered	≈40% gritty - powdery	Abundant	Some
5	Most open; some brown stains	Unaltered	Many altered	All altered	Most altered	≈20-30% gritty - powdery	Many	A few
4	Most open with brown stains	Unaltered	Some altered	Many altered	Some altered	≈10-20% gritty	Some	None
3	Many open with brown stains	Unaltered	Unaltered	Some altered	Unaltered	<10% gritty	A few	None
2	Some open with brown stains	Unaltered	Unaltered	Unaltered	Unaltered	Unaltered	None	None
1	A few open. No stains	Unaltered	Unaltered	Unaltered	Unaltered	Unaltered	None	None
	Tight. No stains	Unaltered	Unaltered	Unaltered	Unaltered	Unaltered	None	None

5) followed by alteration (to sericite and clay minerals) of alkali feldspar phenocrysts (stage 6). Quartz grains are not altered during these stages of weathering, but do disaggregate and reduce in size due to the continual opening-up of grain boundaries and micro-cracks.

Physical properties of different stages of weathering

Physical properties of samples from the different stages of weathering are gradational in nature with some differences between the various stages (Table 4). Unaltered (stage 0), and stage 1 weathered, rhyolite is characterized by large dry unit weights (>25.40 kN/m^3) and dry densities (>2589 kg/m^3), but low apparent porosities (<2.5%). Stage 5 weathered rhyolite, however, is characterized by relatively low dry unit weights (22.98 to 23.54 kN/m^3) and dry densities (2342 to 2400 kg/m^3), but large apparent porosities (8.8 to 11.1%). Stages 2, 3 and 4 weathered rhyolite furthermore, show intermediate, but decreasing, values of dry unit weight and dry density and increasing values of apparent porosity (Table 4). Stages 2, 3 and 4 weathered rhyolite are thus characterized by dry unit weights ranging from 24.09 to 25.39 kN/m^3, dry densities from 2456 to 2588 kg/m^3 and apparent porosities of 2.3% to 11.1%. Stage 6 weathered rhyolite furthermore, shows low values of dry density (<21.90 kN/m^3) and dry unit weight (<2232 kg/m^3) but relatively large apparent porosities (>14.1%).

There is limited variation in the values of the specific gravity (SG) of mineral grains in the different stages of weathering; the SG values ranging from 2.570 to 2.671 (Table 4). This limited range is not unexpected in view of the somewhat similar range in SG values of the main primary and secondary (altered) mineral grains present. Quartz has a SG of 2.65, alkali feldspars a SG between 2.55 and 2.63, plagioclase (andesine) a SG between 2.62 and 2.76, micas (biotite, chlorite and sericite) a SG between 2.61 and 3.3, and kaolinite a SG of between 2.61 and 2.68 (Deer *et al*, 1977).

Uniaxial compressive strength

Samples of the different stages of weathering show some differences in uniaxial compressive strengths with a general decrease with increasing stages of weathering (Table 5). Unaltered (stage 0) rhyolite is characterized by large uniaxial compressive strengths (>125 MPa) whilst stage 1 weathered rhyolite has a lower strength (113 MPa). Stage 2 weathered rhyolite is characterized by uniaxial compressive strengths of between 61.4 and 82.1 MPa, and stages 3 and 4 by relatively low uniaxial compressive strengths of 36.2 to 48.0 MPa, and 16.9 to 29.1 MPa, respectively. Specimens of stages 5 and 6 were unable to be tested as they disaggregated during diamond sawing.

Table 4: Physical properties of different stages of weathering of rhyolite.

Sample Number	Stage of Weathering	Dry Density (kg/m^3)	Dry Unit Weight (kN/m^3)	Specific Gravity	Apparent Porosity (%)
B2	0	2649	25.99	2.640	0.1
B1	0	2648	25.98	2.652	0.5
B7	1	2605	25.56	2.671	2.5
B9	1	2601	25.52	2.642	2.1
B13	1	2589	25.40	2.628	1.9
B3	2	2570	25.21	2.650	3.0
B8	2	2580	25.31	2.660	3.1
B10	2	2588	25.39	2.650	2.5
B5	2	2579	25.30	2.639	2.9
B6	2	2577	25.28	2.622	2.3
B14	3	2541	24.93	2.634	4.2
B12	4	2477	24.30	2.600	5.4
B4	4	2456	24.09	2.594	6.2
B15	5	2400	23.54	2.625	9.3
B17	5	2389	23.44	2.597	8.8
B21	5	2383	23.38	2.607	9.3
B19	5	2379	23.34	2.612	9.5
B16	5	2348	23.03	2.617	11.1
B20	5	2342	22.98	2.614	11.1
B18	6	2257	22.14	2.617	15.1
B22	6	2256	22.13	2.604	14.1
B23	6	2232	21.90	2.570	14.5

DISCUSSION

As weathering proceeds, a 'rock' material will become increasingly decomposed and/or disintegrated until ultimately a 'soil' is formed (Bell, 2000). The terms 'rock' and 'soil' material have been defined in various ways, though for geotechnical purposes, the best definitions are those by Terzaghi & Peck (1948). Terzaghi & Peck (1948, p. 4) have simply defined 'soil' as being "a natural aggregate of mineral grains that can be separated by such gentle means as agitation in water", whilst 'rock' would not be able to be so separated.

In the reduction process of a rock to a soil, various stages can be recognized, though it is almost inevitable that the boundaries between the stages are gradational (Bell, 2000). This is seen in the present study where six sequential, but gradational, changes in visible features, textures and mineralogy can be differentiated in the concentric rings of weathered material formed around core-stones of rhyolite. As noted earlier, weathering starts with the opening-up of grain boundaries and micro-cracks (stage 1) followed by their dark brown staining (stage 2) and the alteration of plagioclase groundmass grains and phenocrysts (stage 3). There is then the bleaching and alteration of biotite flakes (stage 4) followed by the alteration of alkali feldspar groundmass grains (stage 5) and finally alteration of alkali feldspar phenocrysts (stage 6). Quartz grains are not altered during these stages of weathering, but do disaggregate and reduce in size due to the continual opening-up of grain boundaries and micro-cracks.

It is interesting to note that these stages of weathering of rhyolite are very similar to those reported for the weathering of porphyritic biotite granite (Raj, 2022). This similarity is not unexpected for the primary (essential) mineral components of both the rhyolite and the porphyritic biotite granite are similar, though there are differences in textures. As in the weathering of porphyritic biotite granite (Raj, 2022), the stage 6 weathered bedrock material represents the transition between rock and soil material for it comprises natural aggregates that can be

Table 5: Uniaxial compressive strength of various stages of weathering of rhyolite.

Sample Number	Stage of Weathering	Dry Density (kg/m^3)	Uniaxial Compressive Strength (MPa)
C 1	0	2630	143.0
C 2	0	2630	139.8
C 3	0	2630	134.8
C 4	0	2630	125.0
C 5	1	2560	113.2
C 6	2	2610	82.1
C 7	2	2560	78.2
C 8	2	2610	76.7
C 9	2	2560	73.8
C 10	2	2610	71.6
C 11	2	2520	66.8
C 12	2	2570	62.0
C 13	2	2570	61.4
C 14	3	2410	48.0
C 15	3	2430	36.9
C 16	3	2410	36.2
C 17	4	2460	29.1
C 18	4	2450	24.4
C 19	4	2400	16.9

disaggregated when dry specimens are agitated in water (Table 2). In this stage, all the plagioclase phenocrysts and groundmass grains have been altered (to sericite and clay minerals) as have been all alkali feldspar groundmass grains and most phenocrysts (Table 3). Strong bonds between individual mineral grains that existed in the earlier stages of weathering are thus no longer present in the stage 6 weathered bedrock material. Alteration of the groundmass plagioclase and alkali feldspar grains is thus considered to give rise to the loss of bonds between individual mineral grains. The rock - soil transition is furthermore, gradational in nature as shown by decreasing values of dry unit weight, dry density and uniaxial compressive strength, but increasing apparent porosity (Tables 4 and 5).

CONCLUSION

Concentric rings of weathered materials around core-stones show a rhyolite to experience sequential, but gradational, changes in visible features, textures and mineralogy as it transforms from 'rock' into 'soil'. The changes start with the opening-up of grain boundaries and micro-cracks (stage 1) followed by their dark brown staining (stage 2) and the subsequent alteration (to sericite and clay minerals) of plagioclase feldspar groundmass grains and phenocrysts (stage 3). There is then the bleaching and alteration (to chlorite and clay minerals) of biotite flakes (stage 4) followed by the alteration (to sericite and clay minerals) of alkali feldspar groundmass grains (stage 5) and phenocrysts (stage 6). Quartz grains are not altered during these stages of weathering, but disaggregate and reduce in size due to the continual opening-up of grain boundaries and micro-cracks.

Increasing stages of weathering are marked by decreasing dry unit weights, dry densities and uniaxial compressive strengths, but increasing apparent porosities. The transition between 'rock' and 'soil' occurs during stage 6 when all plagioclase groundmass grains and phenocrysts have been altered as have been all alkali feldspar groundmass grains and most phenocrysts. Stage 6 is marked by large apparent porosities (>14%) but low values of dry unit weight (<21.90 kN/m^3) and dry density (<2232 kg/m^3).

ACKNOWLEDGEMENTS

Grateful thanks are extended to the University of Malaya for an F-Vote research grant that provided financial assistance for fieldwork involved in preparation of this article. The anonymous reviewers are gratefully acknowledged for their valuable comments.

CONFLICTS OF INTEREST

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

REFERENCES

Azman, A.G. & Singh, N., 2005. Petrology and geochemistry of the Sempah Volcanic Complex. Bulletin of the Geological Society of Malaysia, 51, 103-121.

Baynes, F.J., Dearman, W.R. & Irfan, T.Y., 1978. Practical assessment of grade in a weathered granite. Bulletin International Association Engineering Geology, 18, 101-109.

Bell, F.G., 2000. Engineering Properties of Soils and Rocks. Blackwell Science Ltd., Oxford. 482 p.

Chakraborty, K.R., 1995. Genting Sempah Volcanic Complex: Genetic implications for the Main Range Granite. Warta Geologi, 21, 216-217.

Cobbing, E.J. & Mallick, D.I.J., 1987. Southeast Asia Granite Project – Field Report for Peninsular Malaysia. Report No. MP/87/19/R, Overseas Directorate. British Geological Survey, 129 p.

Dearman, W.R., 1974. Weathering classification in the characterization of rock for engineering purposes in British practice. Bulletin International Association Engineering Geology, 9, 33-42.

Dearman, W.R., 1976. Weathering classification in the characterization of rock: a revision. Bulletin International Association Engineering Geology, 13, 123-127.

Dearman, W.R., Baynes, F.J. & Irfan, T.Y., 1978. Engineering grading of weathered granite. Engineering Geology, 12, 345-374.

Deer, W.A., Howie, R.A. & Zussman, J., 1977. An introduction to the rock forming minerals. Longman Group Ltd., London. 528 p.

Duzgoren-Aydin, N.S., Aydin, A. & Malpas, J., 2002. Re-assessment of chemical weathering indices: case study on pyroclastic rocks of Hong Kong. Engineering Geology, 63, 99-110.

Duzgoren-Aydin, N.S. & Aydin, A., 2006. Chemical and mineralogical heterogenities of weathered igneous profiles: implications for landslide investigations. Natural Hazards & Earth System Sciences, 6, 315-322.

Haile, N.S., Stauffer, P.H., Krishnan, D., Lim, T.P. & Ong, G.B., 1977. Palaeozoic redbeds and radiolarian cherts: reinterpretation of their relationships in the Bentong and Raub areas, West Pahang, Peninsular Malaysia. Bulletin of the Geological Society of Malaysia, 8, 45-60.

Iliev, I.G., 1966. An attempt to estimate the degree of weathering of intrusive rocks from their physico-mechanical properties. Proceedings 1st International Congress Rock Mechanics, Lisbon, 25 Sept - 1 Oct, 1966. 1, 109-114.

Irfan, T.Y. & Dearman, W.R., 1978a. Engineering classification and index properties of a weathered granite. Bulletin International Association Engineering Geology, 17, 79-90.

Irfan, T.Y. & Dearman, W.R., 1978b. The engineering petrography of a weathered granite in Cornwall, England. Quarterly Journal Engineering Geology, 11, 233-244.

Irfan, T.Y., 1996. Mineralogy and Fabric Characterization and Classification of Weathered Granitic Rocks in Hong Kong. Geo Report No. 41, Geotechnical Engineering Office, Civil Engineering Department, Hong Kong. 159 p.

ISRM, International Society for Rock Mechanics, 1979. Suggested methods for determining water content, porosity, density, absorption and related properties and swelling and slake durability index properties. International Journal Rock Mechanics Mineral Science & Geomechanics Abstracts, Abstracts, 16, 141-156.

ISRM, International Society for Rock Mechanics, 1981. Suggested methods for determining the uniaxial compressive strength and deformability of rock materials. In: Brown, E.T. (Ed.), Rock Characterization, Testing and Monitoring. International Society Rock Mechanics, Pergamon Press, 111-116.

Lee, S.G. & de Freitas, M.H., 1989. A revision of the description and classification of weathered granite and its application to granites in Korea. Quarterly Journal Engineering Geology, 22, 31-48.

Liew, T.C., 1977. Petrology and structural relationships of rhyolitic rocks and micro-granodiorite, east of Genting Sempah, Pahang. Bachelor of Science Honours Thesis, Department of Geology, University of Malaya, KL. 68 p.

Liew, T.C. & Page, R.W., 1985. U-Pb zircon dating of granitoid plutons from the West Coast Province of Peninsular Malaysia. Journal of the Geological Society, 142, 525-626.

Martin, R.P. & Hencher, S., 1986. Principles for Description and Classification of Weathered Rock for Engineering Purposes. Geological Society of London, Engineering Geology Special Publication 2, 299-308.

Melton, M.A., 1965. The geomorphic and paleoclimatic significance of alluvial deposits in Southern Arizona. Journal of Geology, 73, 1-38.

Ollier, C.S., 1965. Some features of granite weathering in Australia. Zeischt Geomorfologie, 9, 285-304.

Onodera, T.F., Yoshinaka, R. & Oda, M., 1974. Weathering and its relation to mechanical properties of granite. Proceedings 3rd Congress, International Society Rock Mechanics, Denver, 2, 71-78.

Parker, A., 1970. An index of weathering for silicate minerals. Geological Magazine, 107, 501-504.

Raj, J.K., 2018. Physical Characterization of a deep weathering profile over rhyolite in humid tropical Peninsular Malaysia. Geotechnical & Geological Engineering, 36(6), 3793-3809.

Raj, J.K., 2022. Rock - soil transition during weathering of a porphyritic biotite granite. Warta Geologi, 48(1), 1–9.

Ruxton, B.P. & Berry, L., 1957. The weathering of granite and associated erosional features in Hong Kong. Bulletin Geological Society of America, 68, 1263-1292.

Singh, N., & Azman, A.G., 2000. Sempah volcanic complex, Pahang. In: Teh, G.H., Pereira, J.J., Ng, T.F. (Eds.), Proceedings Annual Conference 2000, Geological Society of Malaysia, 67-72.

Thomas, M.F., 1974. Tropical Geomorphology - A study of Weathering and Landform Development in Warm Climates. Macmillan Press Ltd., London. 332 p.

Terzaghi, K. & Peck, R.B., 1948. Soil Mechanics in Engineering Practice. John Wiley and Son Inc., US. 566 p.

Uriel, S. & Dapena, E., 1978. Influence of weathering on the mechanical properties of granitic rocks. Proceedings 3rd International Congress, International Association of Engineering Geology, Madrid, 1, 91-104.

Manuscript received 7 April 2023;
Received in revised form 5 August 2023;
Accepted 15 August 2023
Available online 29 November 2023