Article
Vol. 21, No. 3, p. 441–452, June 2017
http://dx.doi.org/10.1007/s12303-016-0060-7
pISSN 1226-4806 eISSN 1598-7477
Geosciences Journal GJ

Evaluation of geomechanical and geochemical properties in weathered metamorphic rocks in tropical environment: a case study from Samanalawewa hydropower project, Sri Lanka

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ABSTRACT: The effect of weathering on changes of physical and mechanical properties of rocks is a prime concern in the perspectives of geology and engineering. These properties have been studied mostly on weathered igneous and sedimentary rocks under humid climates. Studies on weathering of metamorphic rocks, especially under a tropical climate, are rare. This study evaluates change of physical, mechanical, chemical, and mineralogical properties of metamorphic rocks that weather under tropical climatic conditions. Samanalawewa hydropower project area was selected for this study, because rapid weathering of a metamorphic rock (sillimanite garnet gneiss) was observed in the project site. Fresh rocks that are subjected to weathering have reached to completely weathered condition in a time span of less than 25 years in this area. Visually assessed weathering grades were physically and mechanically evaluated using bulk density, equotip hardness, porosity, specific gravity, point load strength, and slake durability tests. Mechanical properties, especially point load strength, change rapidly at the onset of weathering, while chemical properties show significant changes at later stages of weathering. Mineralogical changes such as appearance of secondary minerals are at the latter part of weathering. Physical properties gradually change during weathering. The observed changes in physical, mechanical and chemical properties indicate that their variations during weathering are independent of lithology and climatic conditions.

Key words: weathering grades, rapid weathering, physical properties, mechanical properties, sillimanite-garnet gneiss

Manuscript received October 9, 2015; Manuscript accepted October 17, 2016

1. INTRODUCTION

The rate at which physical, mechanical and chemical properties of a rock change during weathering is a prime concern in geological and engineering perspectives. The evaluation of changes in these properties is one mechanism of assessing the weathering rates (Oguchi et al., 1999). The change in properties could take place within a few years to many hundred years based on prevailing environmental conditions (White and Brantley, 1995). An investigation of rhyolite weathering under temperate climatic condition have reviled that these properties prompt to change at different stages of the entire weathering period (Oguchi et al., 1999). Rock or mineral weathering rates have been estimated based on the experiments, where materials are ranging from atomic scale to watershed (Brantley and Chen, 1995; White and Blum, 1995; Velbel, 1999; White et al., 1999; Hachinohe et al., 2000; Jin et al., 2006; Oguchi, 2013). Velbel (1999) presented that the weathering rate of different minerals is a function of Fe-O bond strength and on ionic potential. Brantley and Chen (1995) reported that temperature is a decisive factor in dissolution of Ca and Mg silicates. Laboratory scale and watershed scale experiments on the effects of climatic variation of granitic rock weathering showed that temperature variation is a very sensitive factor in high release rates of some mobile elements such as Na, K, Ca, Mg and Sr (White and Blum, 1995; White et al., 1999). Furthermore, it is emphasised that laboratory scale dissolution rate determination cannot be extrapolated into natural dissolution rates (Swoboda-Colberg and Drever, 1993; Brantley, 2008). Oguchi (2013) determined weathering rates of andesitic fluvial pebbles by verifying the age of weathering rinds formed.

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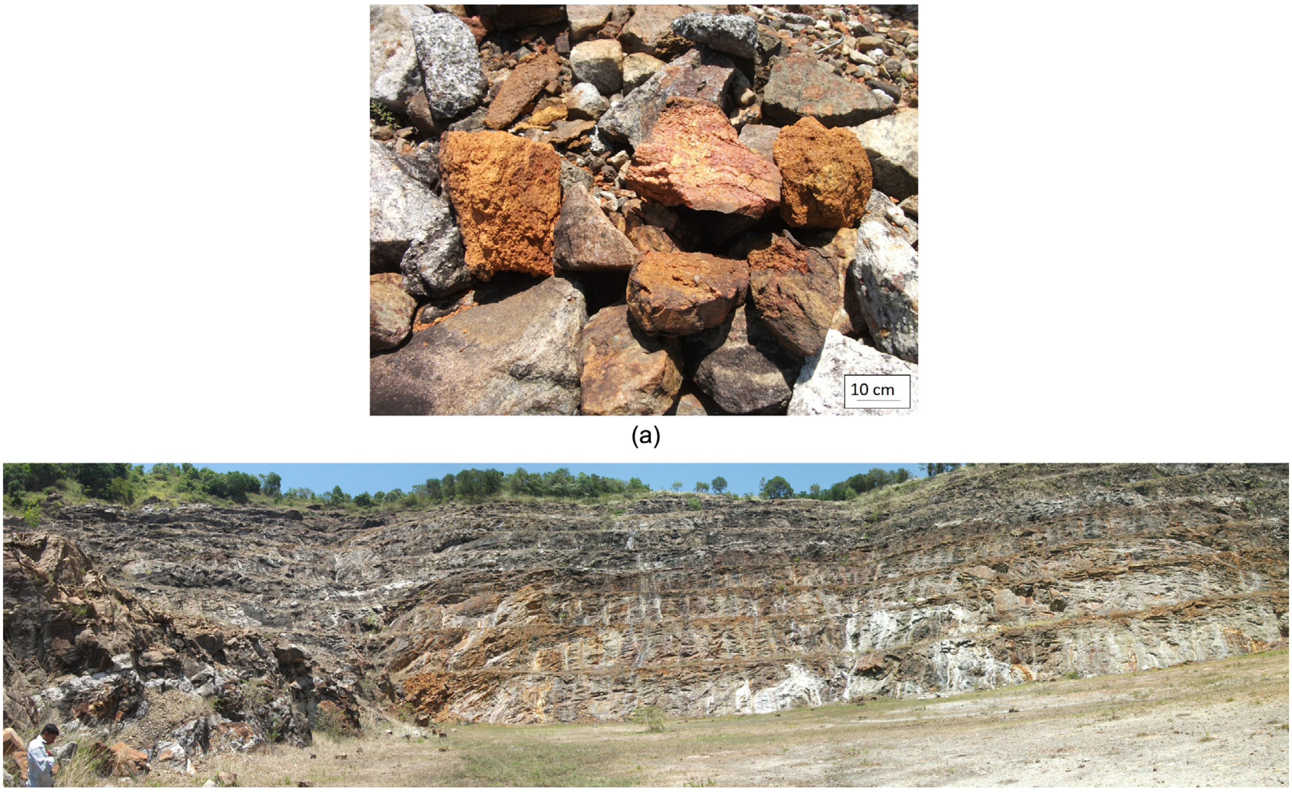
Tating et al. (2013) reported that deterioration due to stress fractures could reduce rock strength by about 20% within a time span less than 10 years in a humid tropical climate. Hachinohe et al. (2000) described rates of change of the thickness of the weathered zone and strength of weathered materials are in 100 year scale for a marine terrace in the Boso Peninsula, Japan.

Samanalawewa hydropower project is considered in this study due to a rapid rate of rock weathering being observed that was first identified in 2005. The extensive weathering of the rocks is regarded as a threat to the stability of the project (Fig. 1a), where rocks were used on the dam slopes. Continuous observations by authors revealed that the weathering could disintegrate only one rock type, sillimanite-garnet gneiss into soil within a period less than twenty-five years that is within the engineering time scale according to Fookes et al. (1988), while other rock types such as charnockitic gneiss, marble and biotite gneisses remain unaltered during that period. Fookes et al. (1988) describes that rock masses subjected to weathering within the engineering time scale, the time in which construction materials would fail, can be considered as a rapid process. He investigated some case studies, where rock materials used as road aggregates had failed within 4 to 5 years. However, most of these rocks are volcanic rocks including basalt (Fookes et al., 1988). All the rocks at the Samanalawewa project are metamorphic and were found to be fresh during excavations at the quarry site (A.A.J.K. Gunatilake – Personal communication). The weathered sillimanite-garnet gneiss exists along with fresh charnockitic gneiss and marble in the quarry site (Fig. 1b).

The weathering rate of sillimanite-garnet gneiss is higher than that reported for different types of rocks (Fookes et al., 1988; Oguchi et al., 1999; Thorn et al., 2002; Matsukura et al., 2007; Tating et al., 2013). Matsukura et al. (2007) estimated rates of weathering using the weight loss method under saturated natural conditions for several different rock types that were made in to pellets. Soft rocks such as limestone and tuff showed about 20% weight loss within a 10 year period, whereas weight loss of crystaline rocks such as granite and schist was negligible during the same time span (Matsukura et al., 2007). A similar research was carried out by Thorn et al. (2002) for limestone, dolomite and granite under near surface weathering conditions. However, overall mass loss rates were less than 1.5% over a five year period. Oguchi et al. (1999) reported that a 60% decrease in compressive strength of porous rhyolite in ten years. Similar weathering rates were reported for alluvial sediments and shale by Tating et al. (2013).

Most studies found in literature address rapid weathering



(a)

(b)

Fig. 1. Weathered surfaces at Samanalawewa hydropower station. (a) The rip-rap zone of the dam where decomposing sillimanite-garnet gneiss is found. (b) Weathered quarry face where rocks were excavated for the rip-rap zone. Weathered rock appears in brownish colour and charnockitic gneiss and marble are in greyish and whitish colour, respectively (Total length approximately 170 m and height approximately 30 m).

of igneous or sedimentary rocks induced by acids, salts or biological factors (Ledin and Pedersen, 1996; Bormann et al., 1998; Chen et al., 2000; Van der Weijden and Pacheco, 2003; Boardman, 2015), but studies of rapid weathering of metamorphic rocks are rarely reported. Therefore, the present study focuses on analysis of changes in physical, mechanical, and chemical properties during weathering and their effects on rapid weathering of a selected metamorphic rock under tropical climatic conditions.

2. STUDY AREA

The Samanalawewa hydropower project site is in Belihul Oya area, about 160 km southeast of Colombo, Sri Lanka (Fig. 2). It consists of a reservoir constructed on the Walawe River, just downstream of the confluence of Walawe River and Belihul Oya. The study area is located in the wet zone, where the average annual precipitation is above 2500 mm, it receives precipitation from both north-eastern and south-western monsoons, but the amount received by the north-eastern monsoon is comparatively less. Inter-monsoon cyclones are another source of precipitation. The temperature ranges from 19 °C to 30 °C throughout the year. The altitude of the area is ranged between 150 m to 650 m above mean sea level with an average of about 530 m, thus the area is physiographically described as midlands (Vithanage, 1970).

Most of the Sri Lankan basement consists of high-grade metamorphic rocks. Miocene limestone that cover the north-western and northern parts of the country and localised sedimentary and igneous rocks account for about 10%. The rest of metamorphic basement rocks are subdivided into four lithotectonic units, ie., the Wanni (WC), Kadugannawa (KC), Highland (HC) and Vijayan (VC) complexes based on geology, geochronology and structure (Cooray, 1994). All these are Precambrian rocks, where sediments deposited about 2.1 Ga ago were subjected to peak metamorphism around 650 Ma at temperatures and pressures about 600–1000 °C and 5–9 kbar, respectively (Cooray, 1994). Rocks in Sri Lanka have been subjected to prolonged weathering since Gondwana to present day under different climatic conditions (Vithanage, 1970; Katz, 1978). The Samanalawewa project area lies within the Highland complex (Vithanage, 1970; Cooray, 1984). The HC-VC lithotectonic

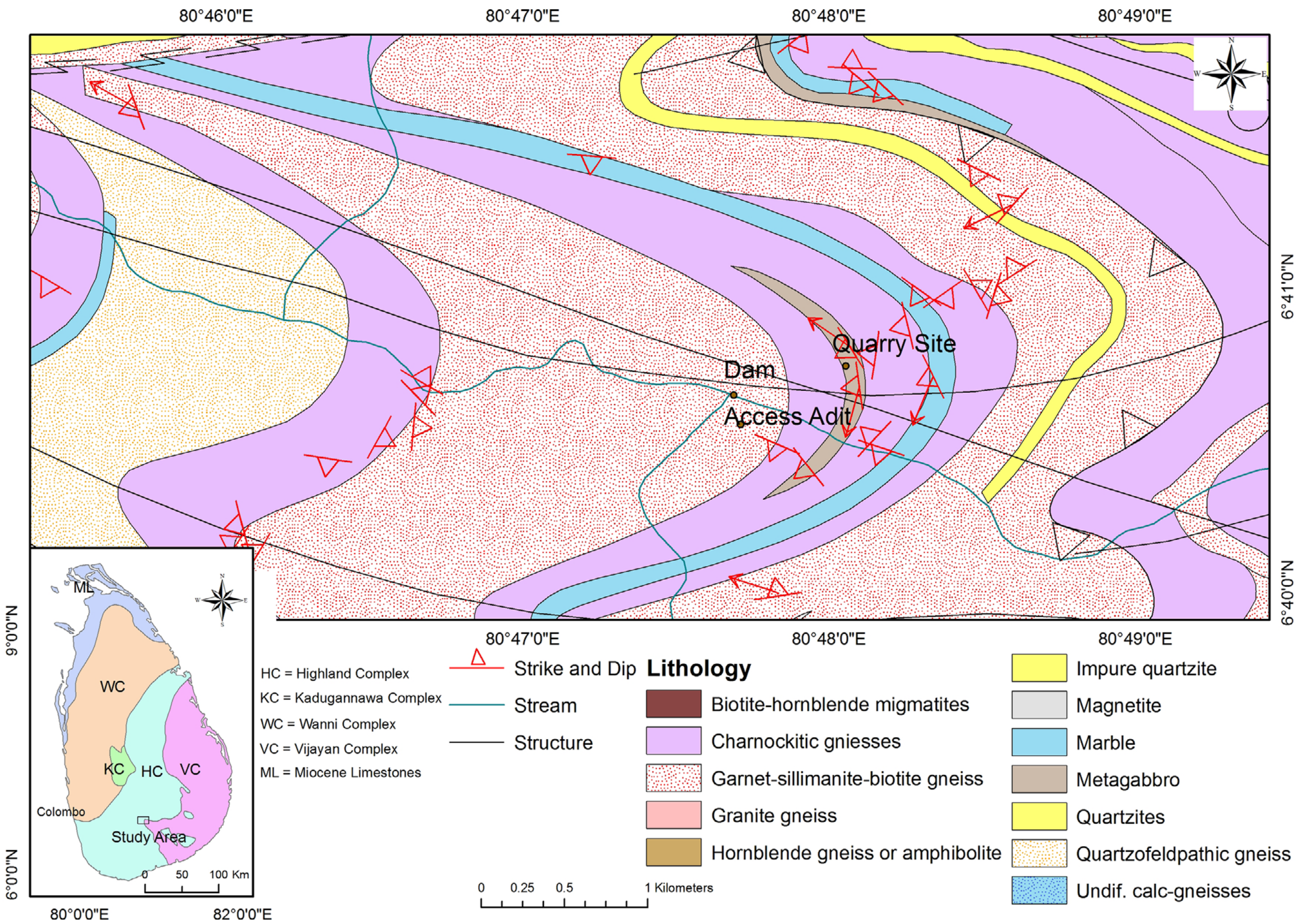


Fig. 2. Inset of simplified geological map of Sri Lanka (after Cooray, 1994), showing location of the investigated area and geological map of the area.

 http://dx.doi.org/10.1007/s12303-016-0060-7

boundary lies to the immediate east of the reservoir (Fig. 2). The metamorphic rocks of Samanalawewa area belong to the Kaltota Formation that consists of four rock types, namely gneisses, granulites, quartzites and marble (Vithanage, 1989; Nagel, 1992). The gneisses are composed mainly of quartz, feldspar and biotite along with sillimanite, amphiboles and pyroxene (Vithanage, 1989).

3. MATERIALS

Based on visual assessment field observations and field tests, rock samples were categorised in to four weathering grades following the ISRM (2007) weathered rock classification scheme (Table 1). The fresh rock was not observed at the quarry site. There are several studies carried out without considering the fresh rock (Guan et al., 2001; Gupta and Rao, 2001; Kim and Park, 2003). The slightly weathered rock (II) shows slight discolouration and stains (Figs. 3a and b). This weathering grade is not ubiquitous in the study area. The colour of the moderately weathered rock (III) has turned into reddish yellow (Figs. 3c and d), some garnets appear in original colour with clearly visible sillimanite and unstained quartz. The rock is highly fractured both parallel and normal to the foliation. Mineral grains are visible to the naked eye such that iron stained quartz and fractured garnet granules are still identifiable in highly weathered rock (IV). Other minerals except graphite, have deteriorated grain boundaries. The completely weathered rock that can be crushed with the fingers (V) is totally discoloured into a reddish colour, but minerals are still bound together as a single unit. Mineral grains such as biotite, graphite, and quartz are easily visible. Traces of the gneissic feature is still illustrated by platy biotite (Fig. 3g).

4. METHODS

Rock samples were collected at the quarry site following methods described in Coe et al. (2010) for the analysis of physical, mechanical and chemical properties. Samples were selected as representative of the intact rocks from locations sufficiently away from the overburden, joints and fractures. The samples represented all weathering grades that were identified employing basic field techniques such as colour, crushability, hammer blow sound, and removal of soils as described by Coe et al. (2010). All are orientated samples and placed in polyethylene bags soon after collection. The samples included rocks of II to V sillimanite-garnet gneiss with replicates. Number of samples were about 15 for category II, IV and V and 12 samples for category III. Weathering grades of samples were quantitatively assessed using physical and mechanical properties estimated from specific gravity, bulk density, porosity, unconfined compressive strength, point load strength, and slake durability tests. These tests were selected in order to exploit their usability to classify weathering grades. Additionally, they are convenient and low cost tests, which can be afforded by researchers in developing countries. The slake durability was selected in this study to assess the abrasion and slaking of the rocks that were undergone loading, unloading and piling for several times during construction phase (A.A.J.K. Gunatilake – Personal communication) and continuous wetting and drying of the rocks at dam slopes due to the fluctuation of change of reservoir water level.

4.1. Physical and Mechanical Properties

Both specific gravity and bulk density are physical properties that can be used to distinguish weathering grades (Irfan and Dearman, 1978a; Patino et al., 2003; Price and Velbel, 2003). The specific gravity of weathered rock of each grade was measured using the pycnometer method (ASTM D 854). The bulk density was determined using the glass bead method initially presented by Consolmagno and Britt (1998) and was successfully tested by Patino et al. (2003) for accuracy and reliability. Sample volume was assessed based on Equation (1).

Table 1. The classification of weathering grades based on field tests and observations. Weathered rocks were classified into four categories based on information extracted from ISRM[(a)] weathered rock classification 2007 (Ulsay and Hudson 2007) and Marques et al. (2010)

Weathering grade	Description	Category
Slightly weathered	Slightly discoloured rock with red and brown staining. Discolouration indicates weathering of rock materials and discontinuity surfaces. Fresh appearance is not still visible. A sharp sound upon hammer blow.	II
Moderately weathered	The rock material is slightly decomposed, but totally discoloured, thus no original colour is there. The rock is present as a continuous framework. A dull sound upon hammer blow, but not easy to break.	III
Highly weathered	Most of the rock material is decomposed with intense discolouration. Discoloured rock is present either as a continuous framework or as coarse stones. All grains are visible to naked eye. The rock mass can be broken by hand in water. even fine grains are visible to naked eye.	IV
Completely weathered	All rock material is decomposed and the original mass structure is still largely intact or with preserved rock texture, the foliation is still defined by biotite grains. Most grains are within the rock aggregate. Mineral grains are visible to naked eye especially graphite. The rock mass can be crumbled with fingers.	IV

[(a)]International Society of Rock Mechanics.

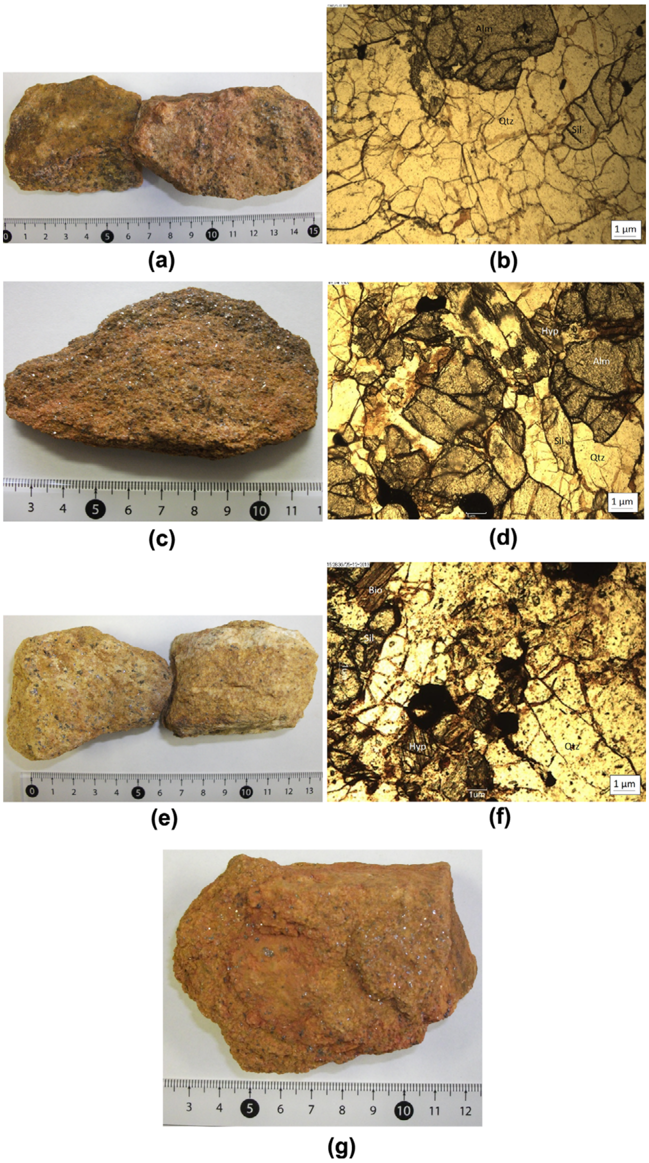


Fig. 3. Weathering grades of sillimanite-garnet gneiss. (a) Slightly weathered rock. (b) Photomicrograph of (a). (c) Moderately weathered rock. (d) Photomicrograph of (c). (e) Highly weathered rock. (f) Photomicrograph of (e). (g) Completely weathered rock. The framework of (g) was not good enough to prepare thin-sections. Photomicrograph were taken under plain polarized light. Intensive fracturing of rocks and decaying minerals are seen in the microimages. (Alm: Almandine, Bio: Biotite, Hyp: Hypersthene, Qtz: Quartz and Sil: Sillimanite).

$$V_r = V_c\,(M_G - M_S + m_r)/(M_G - m_c), \qquad (1)$$

where, V_r is the volume of the sample, V_c is the volume of container, M_G is the mass of the container filled with glass beads, M_s is the mass of the container filled with both glass beads and the sample, m_r is the mass of the sample and m_c is is the mass of the container. Finally, the ratio of m_r to V_r yeilds the density. For all weathering grades mass of samples were kept within the range of 30.00 g to 31.00 g. Since M_s is recognised as the constraint of the precision of this method, each specimen was measured 10 times with beads of 5 mm diameter. (Consolmagno and Britt, 1998; Patino et al., 2003).

The porosity of sillimanite garnet gneiss was measured using Micrometrics® Autopore IV mercury intrusive porosimeter. The average mass of the rock specimen used was 6.5000 g, which was confirmed after several trials as the porosity of the rock was very low. Under the low pressure analysis, the specimen is intruded with mercury up to 31.07 psia, whereas the penetrometer that includes specimen and mercury is undergone confined pressure up to 33,000 psia under high pressure analysis. The porosity is determined with the Washburn Equation (2) using Micrometrics® Autopore IV 9500 Ver 1.15 software.

$$D = \left(\frac{1}{P}\right) 4\gamma\cos\varphi\,, \qquad (2)$$

where, D is the pore diameter, P is the applied pressure, γ is the surface tension of mercury and φ is the contact angle between mercury and the material.

The unconfined compressive strength was measured using the Equotip® hardness tester. The working principle is measuring the mechanical strength of rock upon rebound of a small steel ball dropped on to the surface of the rock (Aoki and Matsukura, 2008). The tester is equipped with spring driven piston, of which the tip is mounted with a tungsten carbide, drops on the material to be tested. The piston that is placed within a coil drops and rebounds generating a current with a voltage, which is proportional to the velocity of moving piston. The ratio of rebound to dropping velocities give hardness that in turn used to calculate the unconfined compressive stress (UCS) (Aoki and Matsukura, 2008). UCS is measured in MPa and Ls is the hardness of the surface of material measured by the device (3).

$$UCS = 8E - 6L_s^{2.5} \text{ (Aoki and Matsukura, 2008).} \qquad (3)$$

The point load strength index test (ISRM, 1985) is used to estimate the degree of weathering of rocks (Broch and Franklin, 1972; Irfan and Dearman, 1978a; Irfan and Dearman, 1978b; Gupta and Rao, 1998). Selected rocks in Sri Lanka have been examined with point load strength index for the same purpose (Jayawardena and Izawa 1994b). The strength of rectangular blocks prepared with dimensions of 5 cm × 5 cm × 6 cm was measured using ELE® point load testing machine in directions parallel to the foliation plane and normal to the foliation plane as specified by Ulusay and Hudson (2007). Completely weathered rocks were not measured, because cutting those into the above-mentioned dimensions was not possible. The rocks were subjected to a maximum load of 20 kN.

The slake durability test (ISRM, 1977) is an indicator of the relationship of mineralogy and durability. It illustrates the deterioration of rocks due to the interaction with water (Franklin

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and Chandra, 1972) and thus, can be utilized to estimate weathering grades (Gupta and Rao, 2001; Dhakal et al., 2002; Kim and Park, 2003). Enkay® slake durability tester was utilized to estimate the slake durability of sillimanite-garnet gneiss. The testing specimen consists of 10 rock lumps, each weighs 80 g, was tested for three 10-minute cycles as per the guidelines given by Franklin and Chandra (1972). Rock lumps were slaked dry and wet by immersing the drum in distilled water, and slaking and rock pieces finer than 2 mm fell into the water. Completely weathered rocks were not tested, because breaking them in to lumps was not possible.

4.2. Chemical and Mineralogical Properties

A specimen of 2 cm × 2 cm × 2 cm dimensions that used for the analysis of chemical properties were prepared in such a way that, the cube contains an even number of mineral layers with similar thickness, in order to minimize the heterogeneity. The cube was powdered using a stainless steel mortar and an agate magnetic agitator. The powdered rock was then passed through a 100 μm mesh sieve and the sample volume was reduced following the quarter splitting method. In order to determine the hygrometric water content (H_2O^-), 2.0 g of powdered rock were heated at 105 °C for 24 h (ASTM D 2216). The constitutional water (H_2O^+) is also an indicator of weathering grade (Jayawardena and Izawa, 1994a) and can be used to assess the quantity of structural water in rocks (Goldich, 1938; Arel and Tugrul, 2001). The H_2O^+ content was estimated using 1 g of powdered sample heated up to 950 °C for 2 h.

The bulk rock geochemical analysis was performed using Phillips® PW 2400 XRF instrument, under the fundamental parameter method using UniQuant 4 software (Thermo Scientific™). A Teflon ring was packed with 5 g of rock and pressed in to a pellet for the analysis. These samples included, 15 samples for each category II, IV and V and 12 samples for category III. Minerals were identified using Rigaku® RINT Ultima III XRD instrument under CuKα radiation (λ = 1.541 Å) with an accelerating voltage of 40 kV, tube current of 25 mA and a scanning speed of 4° 2θ per minute. XRD patterns of bulk samples were recorded between 3° and 40° (2θ) for the analysis of the clay fraction (<2 μm) and 3° to 75° (2θ) for mineral analysis. The surface of each rock sample was observed using JEOL® JV5310 scanning electron microscope in order to study the secondary mineral development.

5. RESULTS AND DISCUSSION

5.1. Physical and Mechanical Properties

Both specific gravity and bulk density gradually decrease with increasing weathering (Table 2). Specific gravity decreases with increasing weathering due to increases in pore spaces and clay content (Tuncer and Lohnes, 1977; Arel and Tugrul, 2001). The bulk density as an indicator of weathering (Grant, 1964), decreases systematically as weathering progresses. The measured bulk density values of the tested rocks are similar to some of other metamorphic rocks, greywacke and basalts, but they are lower than values of granites and quartzites (Irfan and Dearman, 1978a; Hodder and Hetherington, 1991; Irfan, 1996; Gupta and Rao, 2001; Price and Velbel, 2003; Moon and Jayawardane, 2004). Bulk density and point load strength of the tested sillimanite-garnet gneiss show an exponential correlation (Pearson correlation coefficient of 0.95), in consistent with previous studies such as Irfan and Dearman (1978a); Gupta and Rao (1998); Price and Velbel (2003); Moon and Jayawardane (2004). Both bulk density and specific gravity normalized to category II show consistent variations with increasing weathering (Fig. 4a) as illustrated in some other studies (Amada and Okatani, 1991; Oguchi et al., 1999).

The porosity of the rock gradually increases with increasing weathering (Table 2). The thin sections and SEM analysis show that the rocks do not have pores or open fractures, thus very low porosity is resultant even at category V. The porosity of rocks in Sri Lanka have not been studied or published yet, thus these data cannot be compared. Porosity also shows similar variation as bulk density with increasing weathering but in opposite

Table 2. Physical and strength properties

Category	Rock type	Bulk density (gcm^{-3})	Specific gravity	Porosity (%)	UCS (MPa)	PLS Index (MPa)		SD Index (%)	
						⊥	//	Id_1	Id_2
I	Charnockitic gneiss	2.98	2.51	0.9	335	23.6			
II	Sillimanite-garnet gneiss	2.88	2.21	1.5	135	6.0	5.0	99.4	99.1
III	Sillimanite-garnet gneiss	2.80	1.98	2.9	60	1.5	1.0	97.4	94.4
IV	Sillimanite-garnet gneiss	2.70	1.81	4.8	33	0.7	0.6	92.6	78.1
V	Sillimanite-garnet gneiss	2.67	1.72	5.5	11				

UCS – Unconfined compressive strength, PLS – point load strength, SD – Slake durability, ⊥ – Loading direction normal to the foliation, // – Loading direction along the foliation, Id*n* – Slake durability index of nth cycle.
SD of charnockitic gneiss was not measured.
PLS and SD of category V were not measured.

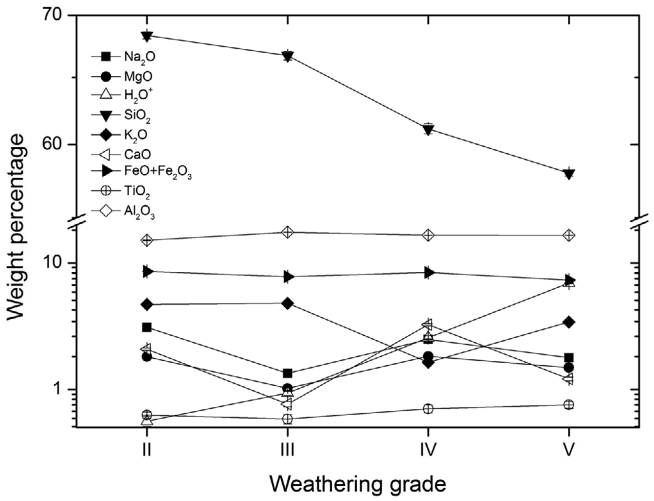

Fig. 4. The average chemical composition at each weathering grade. Error bars indicate the standard deviation.

direction (Fig. 4a). The absence of pores and open fractures indicates that the rock does not promote water infiltration that would accelerate weathering. Thus, surface weathering and denudation are the dominant processes of this rapid weathering.

The change in strength of rock materials during weathering provides a good opportunity to assess the weathering grade. Point load strength, UCS and slake durability show distinct changes at different weathering grades (Table 2). Weathering grades from II to IV show a clear difference in point load strength index in both loading directions (Table 2). At the moderately weathered stage, the rock may have a weaker structure than slightly weathered (Dearman et al., 1978; Jayawardena and Izawa, 1994b). The strength index changes on the loading direction for the same weathering grade. Structural weakness of the foliation plane may be the reason for having a higher point load strength in the direction normal to the foliation of the rock than in the parallel direction. The point load strength index is 1.5 MPa for moderately weathered rocks, which is almost twice as that of highly weathered rocks. The 6.0 MPa value for slightly weathered rocks that is about four times stronger than moderately weathered rocks. The strength difference in both two loading directions decreases as weathering increases due to increase in isotropy. The point load strength index normalized against category II shows a rapid decrease up to moderately weathered rock, followed by a gentle decrease up to highly weathered rock (Fig. 4b) that was already observed by Irfan and Dearman (1978b); Gupta and Rao (1998). Mechanical properties of rocks show rapid change during the incipient weathering (Amada and Okatani, 1991; Oguchi et al., 1999). The point load strength index change from the commencement of Samanalawewa project to present day (25 years) can be used to calculate the rate of change of the point load strength. Thus, the average rate of decrease of point load strength is 0.2 MPa per year. Fresh charnockitic gneiss and marble have higher point load strength indices (Jayawardena, 2011). Furthermore, point load strength indices of fresh Samanalawewa charnockitic gneiss and marble are 23.6 MPa and 6.3 MPa, respectively (A.A.J.K. Gunatilake – Personal communication). In general, point load strength of Sri Lankan charnockite varies between 20 MPa and 65 MPa (Jayawardena, 2003; Jayawardena, 2011) that is higher than sillimanite-garnet gneiss at this site. The point load strength of this rock is nearly similar to that of rocks with similar texture and composition elsewhere in Sri Lanka (Jayawardena, 2011).

The L values and calculated UCS values are comparable with published data on granitic rocks investigated by Hack et al. (1993), Aoki and Matsukura (2008), and Coombes et al. (2013). The UCS values of rocks in Sri Lanka or of metamorphic rocks elsewhere have not been calculated so far using an Equotip device. The USC values shown in the Table 2 follow the similar trend to pint load strength, a sudden change from category II to III followed by a gradual change towards V (Fig. 4b). This test is convenient such that the completely weathered rock could be used for the testing. The data are reliable, since 400 plus reading are included for all weathering grades.

The slake durability of a rock is also sensitive to weathering (Gupta and Rao, 2001; Dhakal et al., 2002; Kim and Park, 2003). There is a clear difference in slake durability between category III and IV grades (Table 2). The durability values do not vary much between category II and III for the first cycle. However, the II has the highest slake durability of 99.1%. This property is considerably lower in category IV. The variation of slake durability of the sillimanite-garnet gneiss is similar to that of gneisses, quartzites, granites and sandstones reported in previous studies (Gupta and Rao, 2001; Dhakal et al., 2002; Kim and Park, 2003; Marques et al., 2010). However, it is clear that slaking does not change rapidly with weathering grades (Fig. 4b). The values obtained for sillimanite-garnet gneiss comply with the Gamble's slake durability classification (Goodman, 1989) in such a way that category II, III, and IV lie in Gamble's categories of high durable, medium high durable and medium durable, respectively. Thus, the slake durability index can be used to classify the weathering grades of this particular rock.

5.2. Chemical and Mineralogical Properties

Weathering enhances secondary porosity and the formation of clay minerals, which in turn gives rise for higher water content. There is a distinct change in the hygrometric water content in each weathering grade, thus, it can be employed to establish the weathering grade. The H_2O^+ content is already used as an

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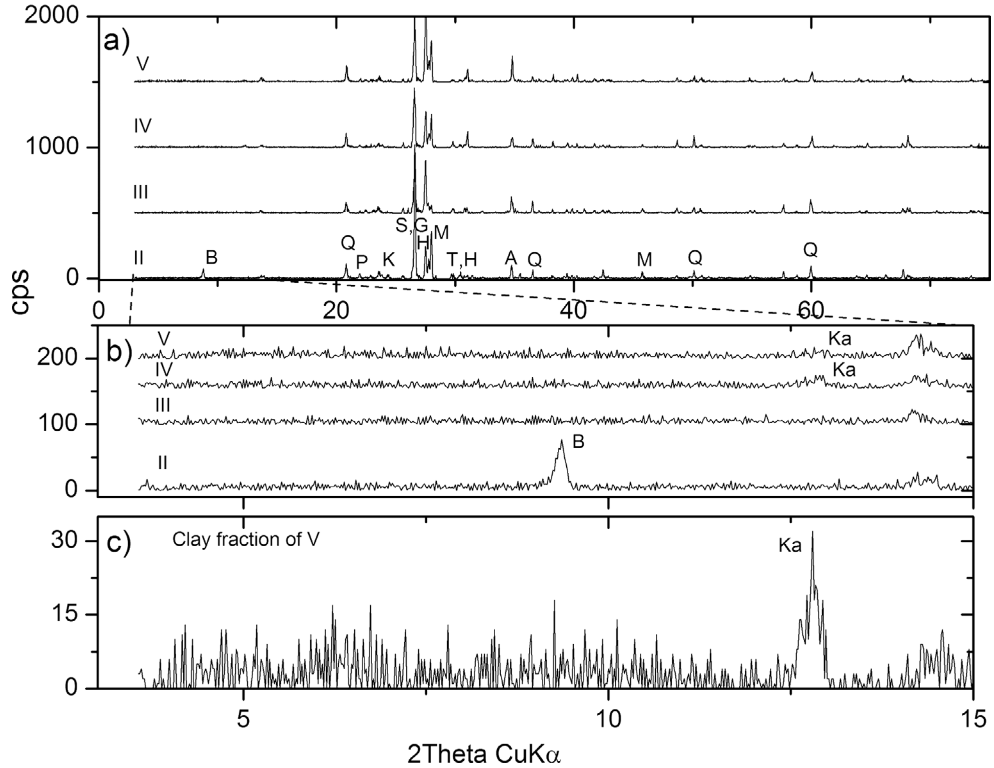

Fig. 5. XRD Patterns. (a) Bulk samples. (b) Enlarged portion of (a) from 0° to 15° 2θ. (c) Clay fraction of V. (Sampling width: 0.02°, Slit 1°-0.3 mm – 1°-0.6 mm). A: Almandine, B: Biotite, G: Graphite, H: Hypersthene, K: K-Feldspar, Ka: Kaolinite, M: Microcline, P: Plagioclase, Q: Quartz, S: Sillimanite, T: Tourmaline.

indicator of weathering grade (Jayawardena and Izawa, 1994a). There is a tendency of formation of clay minerals in highly and completely weathered rocks (Nesbitt and Young, 1982) that is an indicator of the amount of H_2O^+. The XRD patterns of category IV and the clay fraction of category V confirm the presence of kaolinite (Figs. 5b and c). The H_2O^+ values are closely similar to that of other metamorphic rocks in Sri Lanka (Jayawardena and Izawa, 1994a). Additionally, the H_2O^+ content slightly increases from II to IV and followed by a rapid increase to completely weathered rock (Table 3). These changes indicate that chemical properties of a rock change during the moderate stage of weathering as described by Oguchi et al. (1999) and Ma et al. (2007).

The XRF analysis illustrates weight percentage of major oxides

Table 3. Average chemical composition of four weathering grades of sillimanite-garnet gneiss

	II (n = 15) X ± s	III (n = 12) X ± s	IV (n = 15) X ± s	V (n = 15) X ± s	Meta-pelites	PAAS
SiO_2	68.35 ± 0.54	66.72 ± 0.41	61.15 ± 0.31	58.01 ± 0.21	59.1	62.8
TiO_2	0.63 ± 0.02	0.58 ± 0.01	0.70 ± 0.02	0.82 ± 0.01	1.07	1.00
Al_2O_3	15.11 ± 0.31	17.53 ± 0.41	16.57 ± 0.45	16.25 ± 0.30	19.1	18.9
Total Fe	8.59 ± 0.09	7.81 ± 0.11	8.42 ± 0.10	7.34 ± 0.10	9.82	7.2
MgO	1.82 ± 0.95	1.02 ± 0.87	1.83 ± 0.10	1.49 ± 0.90	3.28	2.2
CaO	2.08 ± 0.12	0.77 ± 0.08	3.26 ± 0.08	1.21 ± 0.07	1.25	1.3
Na_2O	2.77 ± 0.15	1.35 ± 0.11	2.49 ± 0.20	1.65 ± 0.11	1.65	1.2
K_2O	4.72 ± 0.19	4.82 ± 0.21	1.64 ± 0.21	3.42 ± 0.15	3.59	3.7
H_2O^+	0.60 ± 0.02	0.92 ± 0.02	2.57 ± 0.01	6.95 ± 0.15	0.51	ng
H_2O^-	0.13 ± 0.01	0.40 ± 0.01	0.70 ± 0.05	0.90 ± 0.01	ng	ng
S	14040.0 ± 152.3	11650.0 ± 140.8	19840.0 ± 162.5	6138.0 ± 135.0	ng	ng

Major oxides in wt% and trace elements in ppm.
Meta-pelites are rocks have similar composition as sillimanite-garnet gneiss (Pohl and Emmermann, 1991) and PAAS is post-Archaean average shale (Taylor and McLennan, 1985) for comparison.
nd: not detected (<10 ppm), ng: not given.
n: number of samples, X: mean, s: standard deviation.

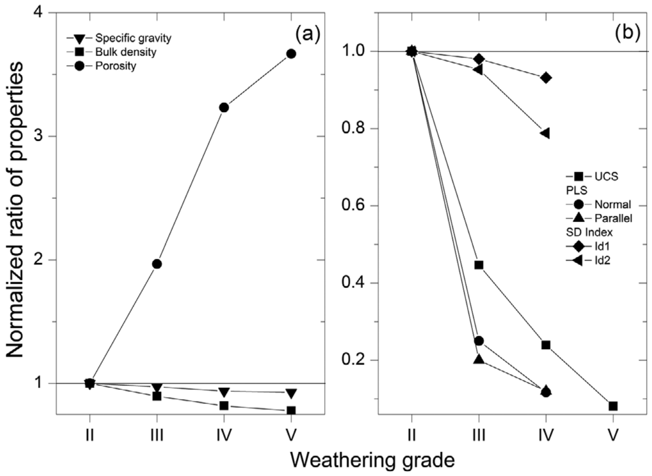

Fig. 6. Variation of rock properties normalized with respect to slightly weathered rock (II). (a) Physical properties. (b) Mechanical properties. (UCS: Unconfined compressive strength, PLS: Point load strength with loading directions normal and parallel to the foliation plane. SD: Slake durability, Id: number of cycles).

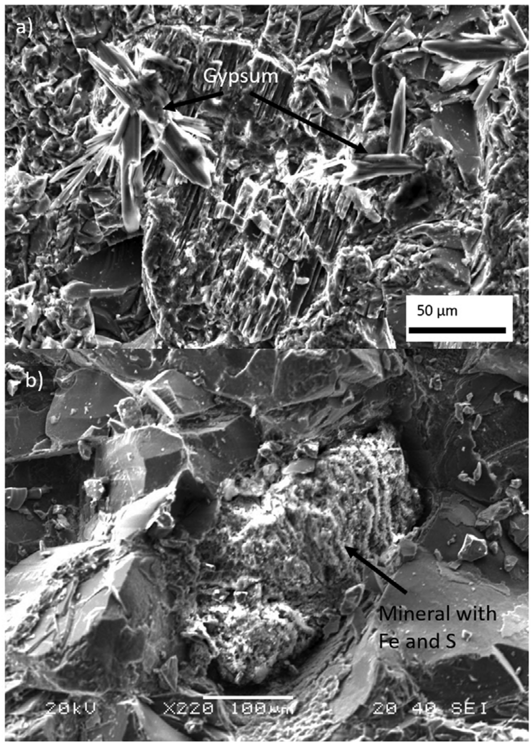

Fig. 7. Scanning electron micrographs (a) Gypsum ($CaSO_4$) on highly weathered rock. Acicular radiated grains are gypsum. (b) The mineral bearing Fe and S.

and selected trace elements. The bulk rock geochemistry indicates that the rock has a felsic chemical composition (Table 3). Oxides of mobile elements such as Na^+, K^+, Ca^{2+}, Mg^{2+} and Si^{4+} show a decreasing trend from category II to V (Fig. 6). However, this is not a gradual decrease. There are some fluctuations in moderately and highly weathered categories. MnO and TiO_2 show an increasing trend towards the category IV rock with some fluctuations (Fig. 6). The weathering of metamorphic felsic silicate rocks do not always produce simple systematic trends in up-profile elemental changes as they have different susceptibility to weathering due to segregation of micaceous minerals and compositional layers (Price and Velbel, 2003). Additionally, the varying percent abundance of minerals at each weathering grade is the reason for inconsistent variation of mobile and immobile elements at each weathering grades (Table 4).

The mobile and immobile elements follow the general behaviour of leaching and enrichment during weathering. However, unusual changes of Na, K, Ca and Mg occur in moderately and highly weathered rocks due to the change in mineralogy such that heterogeneous existence of minerals such as K-feldspar, plagioclase, biotite and gypsum (Table 4; Fig. 7a). It is not an unusual behaviour as described by Price and Velbel (2003) that weathering of felsic metamorphic rocks do not show a systematic change in elements. However, gypsum ($CaSO_4$) that is not indicated in XRD patterns was observed only on the surface of IV, which should be the reason of high CaO (Fig. 7a). The higher amount of sulphur is present due to gypsum and the other mineral with Fe and S, 45% and 55%, respectively that observed only under SEM (Fig. 7b). K_2O and Na_2O showing a complex mobility during weathering as described by Harnois (1988). The vulnerability of plagioclase and resistance of K-feldspars at early weathering explain this behaviour (Duzgoren-Aydin and Aydin, 2003). TiO_2 shows characteristic gradual enrichment due to its immobility as illustrated in Harnois and Moore (1988).

Normalized ratios of each oxide at each weathering grade show the rate of depletion or enrichment with increasing weathering (Fig. 8). Except for CaO and K_2O, other mobile elements show a similar behaviour. Being highly mobile elements, CaO and Na_2O have leached early showing a higher depletion as weathering progresses (Fig. 8) (Anderson and Hawkes, 1958;

Table 4. The percent abundance (%) of minerals in each weathering grades of sillimanite-garnet gneiss based on the observations of hand specimens, thin-sections and SEM analysis

	II	III	IV	V
Quartz	30	30	30	30
K-Feldspar	30	20	25	–
Plagioclase	5	15	10	–
Almandine	14	12	12	–
Sillimanite	9	10	10	–
Biotite	3	1	5	–
Hypersthine	4	6	1	3
Graphile	3	4	2	4
Rutile/Illmanite	2	2	2	–
Gypsum	–	–	3	–

–: not observed.

http://dx.doi.org/10.1007/s12303-016-0060-7

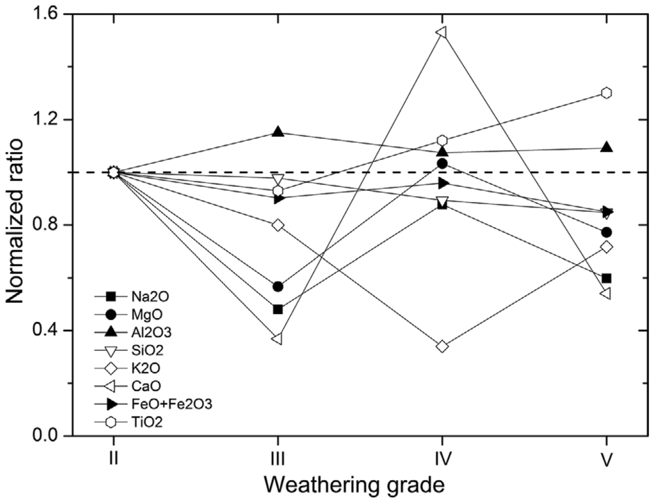

Fig. 8. Oxides concentrations normalized with respect to II at each weathering grade.

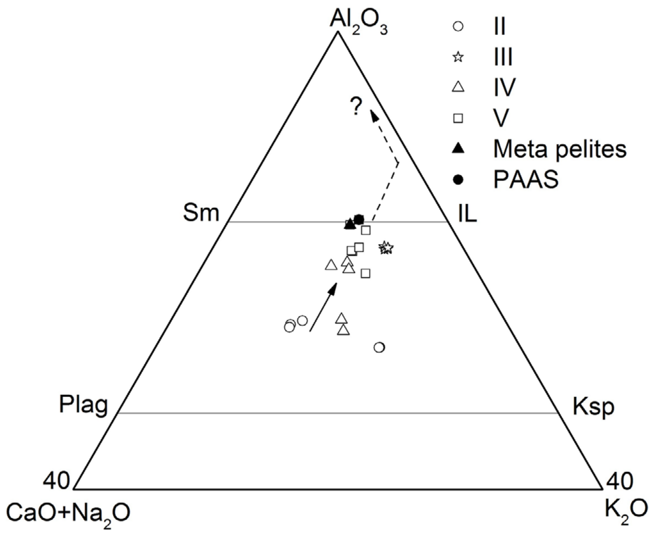

Fig. 9. A-CN-K diagram shows the present weathering trend. The dashed arrow predicts the direction of further weathering. A: Alumina, CN: CaO + Na_2O, and K: K_2O (All in mole percentage). Metapelites (MP) and PAAS are plotted along with V though those are fresh rocks. Higher alumina and lower K_2O contanets of MP and PAAS deviates them from sillimanite-garnet gneiss. Plag: Plagioclase, Ksp: K-Felpdspar, Sm: Smectite, IL: Illite. Lower part of the diagram is not illustrated since no data is plotted.

Taylor and McLennan, 1985; Rollings, 1993). Lesser depletion is shown by MgO at the same weathering grades could be due to their moderately high ionic potential (Rollings, 1993).

The A-CN-K diagram also shows that rocks have not reached the A-K line, ie. K_2O has not been subjected to leaching as much as Na_2O and CaO have (Fig. 9). Although there is a significant K-feldspar content in all samples, the weathering trend, which is parallel to A-CN line, still follows the direction predicted by Nesbitt and Young (1984). Metamorphic rocks elsewhere show similar weathering trends (Aristizábal et al., 2005). The weathering trend shown in Figure 9 is difficult to predict after III.

Mineralogical and chemical properties of a rock show changes from moderate to later stages of weathering (Amada and Okatani, 1991; Oguchi et al., 1999). The same phenomenon is observed in the present study that indicates the chemical behaviour of metamorphic rocks weathered at tropical climate, where temperature and mean annual rain fall range 18 to 30 °C and 900 to 4500 mm, respectively, is similar to that of rocks weathered in temperate climates, where temperature and mean annual rain fall range –20 to 28 °C and 1000 to 4000 mm, respectively, studied by (Ruxton, 1968; Oguchi et al., 1999; Price and Velbel, 2003).

The overall rate of depletion of elements such as Na, K, Ca, Fe, Ni, and Si within 25 years is incomparable to PAAS. Only extreme weathering could make such a depletion of elements (Middelburg et al., 1988). Their concentration in slightly weathered rock are higher than that of PAAS, whereas, in completely weathered stage it is lower. The removal of elements in larger quantities significantly reduce the strength of the mineral structure (Moon and Jayawardane, 2004).

6. CONCLUSIONS

This study focuses on rapid weathering phenomena observed on metamorphic rocks in Sri Lanka, where humid tropical climatic conditions prevail. It could be deduced that the rapid removal of elements compared to weathering of PAAS has weaken the mineral structure that consequently, made the rock vulnerable to weathering. In considering the relationships between rock properties and weathering grades, mechanical properties are the best indicators of weathering grades in comparison to physical, chemical, and mineralogical properties. The measured values of point load strength and unconfined compressive strength decline rapidly onset of weathering. Physical properties such as bulk density, porosity and specific gravity change gradually with increasing weathering. The bulk rock chemistry changes significantly in the latter stages of weathering. The behaviour of above mentioned properties indicate that their change during the wreathing of metamorphic rocks under the humid tropical is same as that of other rock types under humid climatic conditions. The effect of changes in these properties on rapid weathering is not convincing.

ACKNOWLEDGMENTS

This study is a part of DTU's doctoral study that is financially aided by a Japanese government Monbukagakusho scholarship to DTU from Saitama University, Japan. We express our sincere gratitude to Mr T.M.S.K. Thilakarathna, DGM of Samanalawewa

Complex (SHEP) of Ceylon Electricity Board (CEB), Sri Lanka for granting permission to access the SHEP facility and to the staff of the JVS Dam Monitoring Office for assisting during fieldwork. Authors are grateful to Dr. Jeevan Jayakody, Department of Geosciences, University of Nevada, LV for his kind assistance on reading and correcting the manuscript language.

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