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Chemical and mineralogical weathering indices applied to weathering crust developed on the Dai Loc granitoids in A Luoi area, Central Vietnam

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ABSTRACT

This paper presents a compilation of mineralogical weathering indices (X_d values, a quantitative mineralogical measure of decomposition of feldspar against quartz) and chemical weathering indices including Ruxton Ratio (R), Weathering Index of Parker (WIP), Chemical Index of Alteration (CIA), Chemical Index of Weathering (CIW), Plagioclase Index of Alteration (PIA), Silica-Titania Index (STI), Product Index (PI) and Mobile Index (I_{mob}) for a weathering crust developed on the Dai Loc granitoids in A Luoi area (Central Vietnam). The granitoids exposed as narrow bands along the Dakrong - A Luoi fault system have been moderately to highly altered due to effects of weathering conditions. Mineralogical composition of the weathered layers essentially includes illite, quartz, kaolinite, feldspar, goethite and chlorite. Total silica, aluminum and iron oxide contents of the altered products vary from 88.9 wt.% to 91.0 wt.% indicating a sialferit-typed weathering crust. The results reveal that these indices could be basically applied to characterize grade of weathering by incorporating major element chemistry and mineral distribution. X_d values of all examined layers are greater than 0.5, ranging from 0.66 (saprolite layer) to 0.92 (clayey mottled layer), implying that weathering and leaching has sharply reduced the feldspar content of the original rock. R, WIP, STI, PIA and Wp indices decrease whilst CIA, CIW, PI and I_{mob} increase corresponding to a gradual alteration from saprolite layer to surface soil layer.

Keywords: A Luoi, Dai Loc granitoids, weathering indices.

1. Introduction

Weathering is generally defined as the process of alteration and breakdown or dissolving of rocks and minerals on Earth's surface by physical, chemical and/ or bio-effects (*Selby, 1993*).

Chemical weathering indices are based on whole rock major element compositions and referred to as indices of alteration. Most of them are expressed as molecular or weight percentage ratios between various groups of major oxides. These indices have facilitated research on the geochemistry of the Earth's surface environment over geologic time, evaluation soil fertility and development and so on, and have been widely used to characterize a certain systematic alteration of weathering profiles at depths (eg. *Tugrul and Gurpinar, 1997; Price and Velbel, 2003; Haskins, 2006; Ceryan, 2008*). Ideally, a chemical index should permit comparison between studies performed at different localities, on different materials and on weathering profiles of different ages. Common chemical weathering indices are Ruxton Ratio (R, *Ruxton, 1968*), Weathering Index of Parker (WIP, *Parker, 1970*), Chemical Index of Alteration (CIA, *Nesbitt and Young, 1982*), Chemical Index of Weathering (CIW, *Harnois, 1988*), Plagioclase Index of Alteration (PIA, *Fedo et al., 1995*), Silica-Titania Index (STI), Product Index (PI, *Reiche, 1943*) and Mobile Index (I_{mob}, *Irfan, 1996*)...

In a similar manner to chemical weathering indices, mineralogical indices can be an effective tool to assess the weathering of rocks based on ratios of sustainable and sensitive minerals. Lumb (*1962*) proposed a quantitative mineralogical measurement of decomposition degree called X_d value, which is defined as follows:

$$X_d = \frac{N_q - N_{qo}}{1 - N_{qo}} \qquad N_q = \frac{\%Quartz}{\%Quartz + \%Feldspar}(soil) \qquad N_{q0} = \frac{\%Quartz}{\%Quartz + \%Feldspar}(freshrock)$$

As X_d less than 0.5, the microfabric consists of an interlocking granular aggregate enclosing isolated

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decomposed minerals (granular framework). As X_d approaches 0.5, the microfabric develops into a framework of fresh rocks containing decomposition products. As X_d is greater than 0.5, the microfabric is dominated by the decomposition products which enclose remnant original rocks. If $X_d = 1$, weathering and leaching has reduced the feldspar content to zero, and the soil can be considered to be in a state of advanced weathering.

Vietnam belongs to humid tropical monsoon climate, exposed rocks thus have been strongly weathered generating diverse products, which reflect different types and degrees of weathering. The A Luoi area is widely covered by magmatic rocks of the Dai Loc complex including granite, gneissogranite, granite aplite and pegmatite, which spread as narrow bands along the Dakrong - A Luoi fault zone (*Nguyen Van Trang et al., 1995; Hoang Hoa Tham et al., 2009; Tran Van Tri and Vu Khuc, 2009; Quach To Kim, 2010*). Under weathering conditions, the rocks have been undergone an alteration, which is revealed in color, grain-size, texture, mineral and chemical compositions. The aims of this work is to provide typical characteristics involving mineral and chemical compositions of the Dai Loc granitoids in A Luoi area, and an employment of weathering indices for evaluating their grade of weathering.

2. Study area

The A Luoi area is located in the South-western part of Thua Thien Hue province (Central Vietnam). It is mostly covered by soil and represents highly dissected topography with moderate to dip slopes. In the geological map, A Luoi has a thick stratigraphic succession of Neoproterozoic - Cambrian and Cambrian - Ordovician schists; Ordovician - Silurian shale, siltstone, sandstone and tuff; and Permian sedimentary rocks. Quaternary sediments predominantly distribute along streams and rivers. Nearly all magmatic rocks in the area is acidic, of which the Dai Loc complex is the most predominant. The rocks are exposed as narrow bands along the Dakrong - A Luoi fault zone and composed of three phases. The first phase includes medium-grained porphyritic two-mica gneissogranite, melanocratic coarse-to medium-grained two-mica gneissogranite; the second phase includes fine- to medium-grained two-mica gneissogranite; the last phase mainly includes veins of aplite granite, pegmatite bearing large mica and aplite (*Fig. 1*) (*Nguyen Van Trang et al., 1995; Hoang Hoa Tham et al., 2009; Tran Van Tri and Vu Khuc, 2009; Quach To Kim, 2010*).

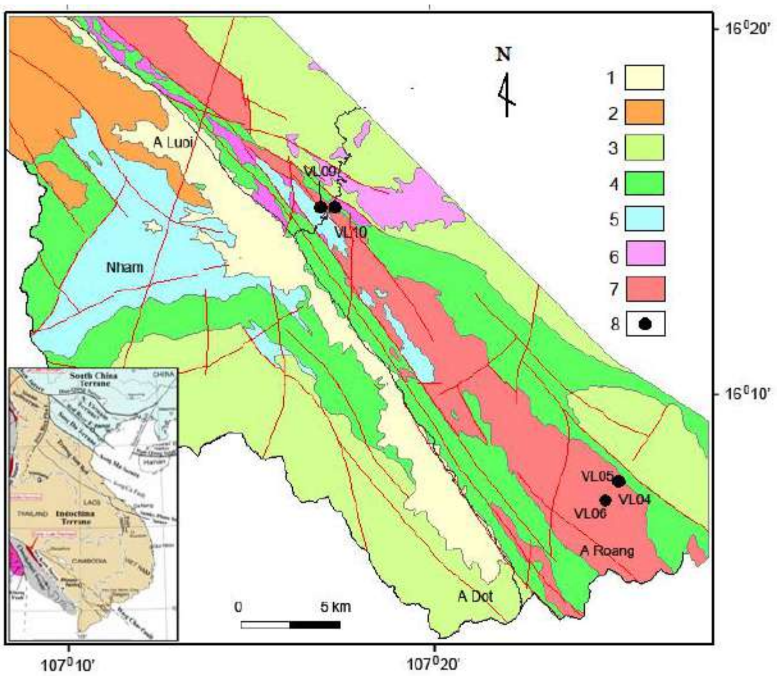

Fig. 1. *Geological map of A Luoi area and sampling sites (modified after Nguyen Van Trang et al., 1995), the inset was modified from Metcalfe (2011).*

1. *Quaternary sediments;*
2. *Permian sedimentary rocks;*
3. *Ordovician - Silurian shale, siltstone, sandstone and tuff;*
4. *Cambrian - Ordovician schists;*
5. *Neoproterozoic - Cambrian schists;*
6. *Permo-Triassic gabbrodiorite, diorite;*
7. *Silurian - Devonian gneissogranite, granite aplite;*
8. *Sampling sites.*

Climatically, the area is humid tropical monsoon with hot dry summers and cool wet winters characterized by annual average temperature of 26-28 ^{0}C and 20-24 ^{0}C in summer and in winter, respectively. The monsoon is the main cause of high precipitation in winter, which starts from September to February of next year with about 60-70 % of the annual rainfall. Landslide phenomena in the area often occur from October to December due to tropical low-pressures or storm/ typhoons.

3. Methodology

3.1. Field investigation

Geological and geomorphological investigations were executed at weathering crust outcrops developed on the Dai Loc granitoids, which were mostly found along slope cuts. Sampling locations were selected to obtain a range of materials through the profiles and sampling intervals within the profiles was basically determined due to difference in color, texture of each layer.

3.2. Lab work

Grain size distribution of soil materials was determined at the Geotech laboratory (Hue University of Sciences) using a combination of sieve analysis for sand fractions and pipette method for mud fractions as followed by a Vietnamese standard TCVN 4198:1995 for Laboratory methods of determination of grain size distribution.

Mineralogical and chemical analyses were carried out at Institute of Geology (Vietnam Academy of Sciences and Technology). About 400 grams of dried bulk samples was broken by a small hammer and hand crusher primarily to reduce the rock aggregate to smaller particles and finally to get the powder samples. Mineral composition of different weathering stages was determined using an Empyrea Panalytical X-ray diffraction. Concentrations of major and trace elements were determined by a S4 Pioneer wavelength-dispersive X-ray fluorescence spectrometer using a powder-bead method.

4. Results and discussions

4.1. Description of weathering profile developed on the Dai Loc granitoids

Field observation has revealed that the examined outcrops developed on the gneissogranites provide clearly differentiated layers (VL04, VL06 and VL10), of which the VL10 is the most typical weathering profile since it presents a relatively complete weathering sequence from fresh rock to completely weathered soil. Hence, in this paper the description was only made for the VL10 profile.

The VL10 is exposed on a talus of the route No. 49 from Hue city to A Luoi, which has been developed over the medium-grained porphyritic two-mica gneissogranite, melanocratic coarse-to medium-grained two-mica gneissogranite of the Dai Loc complex. Slope dip is about 40 degrees. Based on visual characteristics such as color, texture and grain size of the weathered products, the profile can be divided into five weathering layers (*Fig. 2*).

VL10-L1 (Top layer): Completely weathered products have a yellow color, lying beneath plant layer and containing some tree roots. The soil is moderately smooth and soft since comprising an amount of small grained quartz. Thickness 0.3-1.0 meters.

VL10-L2: The weathered products have a brownish-yellow color and contain a number of yellow spots altered from large feldspar crystals. At places, there have hard darkish brown iron-rich curds. Nevertheless, the soil is generally more smooth and softer than that of the VL10-L1. Thickness 2.0-2.5 meters.

VL10-L3: This is likely a lens comprised a number of coarse hard curds.

VL10-L4: This is a highly weathered layer and is slightly similar to the VL10-L2 since the weathered materials are brownish yellow in color and have yellow clusters of completely altered feldspars. Residual fragments are also coeval and somewhat retain texture of the mother rocks. Thickness 1.0-1.5 meters.

VL10-L5: Slightly to moderately weathered gneissogranites composed of large greyish yellow blocks of 10-15 cubic meters. The products retain porphyritic gneiss texture of the mother rocks. Thickness 4.0-5.0 meters or more.

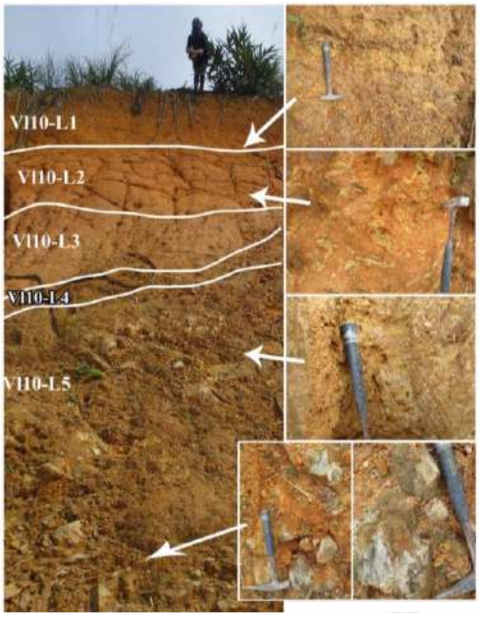

Fig. 2. *Weathering profile of VL10.*

Grain size distribution of the VL10 profile's layers is characterized by a high concentration of fine-grained fractions (silt and clay) of above layers compared with below ones. Grain size concentration is closely related to weathering intensity (*Fridland, 1973; Nguyen Thanh Van, 1984; Pecsi and Richter, 1996; Nguyen Van Pho, 2013*) which is expressed by soil weathering index K_d. Low K_d values correspond to a strongly weathered grade; inversely, a high Kd value states a weakly weathering (*Pecsi and Richter, 1996*). As can be seen in Table 1, K_d index of the VL10 increases from 0.45 (completely weathered grade - VL10-L1) to 2.32 (highly weathered grade - VL10-L4) supporting a common alteration of weathering crust developed on magmatic rocks.

Table 1. Grain size distribution (wt.%) of weathered layers developed on the Dai Loc granitoids

Sample	**Grain size (mm)**							**Kd**
	10-2	**2-0.5**	**0.5-0.25**	**0.25-0.1**	**0.1-0.05**	**0.05-0.005**	**<0.005**	
VL10-L1	0.40	5.00	2.70	0.10	23.1	67.5	1.30	0.45
VL10-L2	1.90	8.00	3.40	0.30	22.8	58.7	4.90	0.57
VL10-L3	3.70	19.3	9.60	1.30	30.4	33.9	1.70	1.81
VL10-L4	3.90	19.9	9.10	1.00	36.0	24.4	5.70	2.32

4.2. Chemical weathering indices for the Dai Loc weathering crust

From chemical compositions and chemical weathering indices of the Dai Loc weathering crust presented in Table 2, it was found that significant chemical changes have occurred during weathering for all the major elements. Particularly, the altered materials are distinguished by a high concentration of Si, Al and Fe compared with mother rocks. Total SiO_2, Al_2O_3 and TFe_2O_3 contents are up to 88.9-91.0 wt.%, and plotted within Sialferit field in a chemical ternary diagram for weathering crust types reported by Nguyen Thanh Van (*1984*) (see *Tran Van Tri and Vu Khuc, 2009*).

Table 2. Chemical composition and weathering indices of weathered layers developed on the Dai Loc granitoids.

Chemical composition						**Weathering Index**					
Sample	**VL10-L1**	**VL10-L2**	**VL10-L3**	**VL10-L4**	**DLG (*)**	**Sample**	**VL10-L1**	**VL10-L2**	**VL10-L3**	**VL10-L4**	**DLG (*)**
SiO_2	63.19	52.32	62.17	62.94	69.49	R (Si/Al)	3.00	1.84	2.45	2.62	4.83
TiO_2	1.05	0.69	0.54	0.90	0.39	WIP	-0.76	-4.41	-2.38	-2.09	10.37
Al_2O_3	21.03	28.48	25.4	24.06	14.40	CIA	85.80	90.59	88.50	88.29	60.45
TFe_2O_3	6.77	8.13	2.88	3.42	6.34	CIW	84.12	89.89	87.31	86.86	53.48
MnO	0.01	0.01	0.01	0.04	0.08	PIA	95.44	97.05	97.42	99.01	64.93
MgO	0.02	0.02	0.01	0.02	1.06	STI	72.32	63.75	69.94	70.44	81.02
CaO	0.87	0.79	0.59	0.20	2.92	PI	68.65	58.38	68.33	68.92	76.68
Na_2O	0.01	0.01	0.01	0.01	2.93	Wp	27.78	24.15	28.17	29.86	1708.2
K_2O	2.60	2.16	2.70	2.98	3.57	I_{mob}	0.63	0.69	0.65	0.66	0
P_2O_5	0.06	0.03	0.03	0.04	0.11						
SO_3	0.04	0.07	0.04	0.04	-						
LOI	4.23	7.06	5.55	5.19	-						

(*) DLG - Fresh gneissogranite of the Dai Loc complex reported by Tran Van Tri and Vu Khuc (2009).

The chemical change among layers of the VL10 profile shows that SiO_2 and K_2O contents gradually increase from VL10-L2 (52.32 wt.% and 2.16 wt.%, respectively) to VL10-L4 (62.94 wt.% and 2.98 wt.%, respectively); whereas Al_2O_3 content reduces progressively from 28.48 wt.% (VL10-L2) to 24.06 wt.% (VL10-L4) (*Tab. 2, Fig. 3*). SiO_2 content of the mother rock is significantly higher than that of altered materials.

It also can be seen that a relationship exists between the weathering indices and grade of weathering. In general, values of R, WIP, STI and Wp increase from top layers to saprolite and fresh rock layers, corresponding to a progressively weak weathering grade towards the beneath (*Tab. 2, Fig. 4*). Excepting the top layer, probably due to a relative enrichment of residual quartz since a relative movement of clay fraction, variation of all weathering indices manifests a weathering grade. This suggests that titanium has been accumulated during weathering, whereas most of Mg^{2+}, Na^{+} and Ca^{2+} cations were leached and moved out during weathering process, only a moderate amount of Mg^{2+} was remained to form chlorite and clay minerals.

Contrary to R, WIP, STI, PIA and Wp, CIW, CIA and I_{mob} values gradually decrease with depth implying that calcium, sodium and potassium are generally removed from the feldspars during weathering by aggressive soil solutions. In addition, the proportion of alumina to alkalis is typically increase in the weathered products, ranging from 4.0 (fresh rock) to 8.1 (saprolite layer) and 13.2 (clayey mottled layer). This agrees with a decline trend of potassium, sodium and calcium contents during weathering caused by an alkalis adsorption on clays through ion exchange, whilst sodium and calcium cations were steadily dissolved and taken out of the weathering crust (*Tab. 2, Fig. 4*).

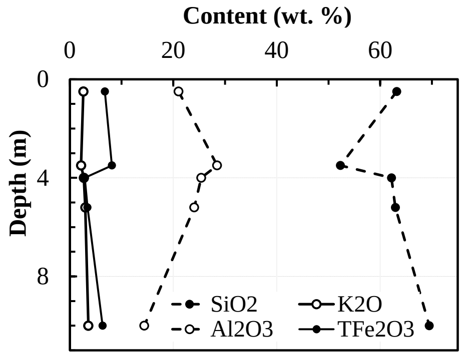

Fig. 3. Variation of oxide contents at depths.

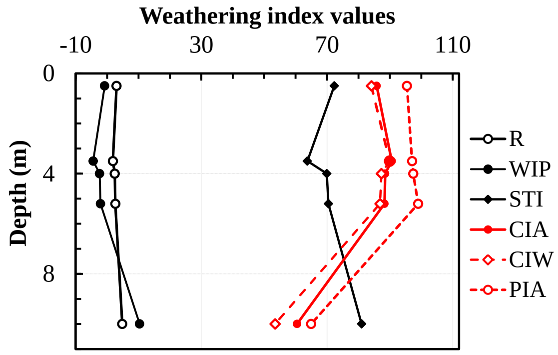

Fig. 4. Variation of weathering indices at depths

4.3. Mineralogical weathering indices for the Dai Loc weathering crust

Table 3 and Figure 5 provides a summary of mineralogical composition and mineralogical weathering indices for the Dai Loc granitoids and its products at various depths.

XRD data for all analyzed samples give a major mineral composition of illite (12-15 wt.%), kaolinite (12-35 wt.%), quartz (38-58 wt.%), feldspar (2-11 wt.%), chlorite and goethite (6-7 wt.%). In comparison with mineral constituent of the Dai Loc gneissogranites, which mainly include feldspar, quartz, plagioclase, biotite and muscovite (*Tran Van Tri and Vu Khuc, 2009*), this modification indicates that the illite and kaolinite are generated from feldspar and muscovite. An increasing quartz content (58 wt.%) of VL10-L1 is probably attributed to partial erosion of kaolinite and goethite out of the top layer due to surface water.

N_q and X_d values obviously tends to rise from the saprolite (0.79 and 0.66, respectively, VL10-L4) to the top layer (0.94 and 0.89, respectively, VL10-L1). This trend is commonly observed in weathering products of acidic bedrocks (*eg. Haskin, 2006*). The high N_q and X_d values of VL10-L2 (0.95 and 0.92, respectively) correspond to a low concentration of feldspar as a result of alteration into clay minerals.

Table 3. Mineral composition (wt.%) of weathered layers developed on the Dai Loc granitoids.

Sample	VL10-L1	VL10-L2	VL10-L3	VL10-L4	DLG (*)
Quartz	58	38	46	42	20-25
Feldspar	4	2	7	11	30-40
Illite	15	12	15	15	
Kaolinite	12	35	22	22	
Chlorit	4	4	5	4	
Goethite	2	3	2	3	
N_q	0.94	0.95	0.87	0.79	
N_{qo}					0.39
X_d	0.89	0.92	0.78	0.66	

(*) DLG - Fresh granites of the Dai Loc complex reported by Tran Van Tri and Vu Khuc (2009).

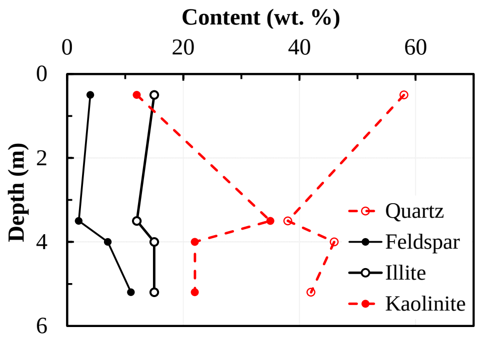

Fig. 5. Variation of mineral contents at depths.

5. Conclusions

The study of weathering profile developed on the Dai Loc granitoids (A Luoi area, Central Vietnam) involving chemical and mineralogical weathering indices could lead to the following major conclusions:

1. The described profile is typical for weathering crust on Dai Loc granitoids in A Luoi area, consistin of fresh rock, weakly weathered zone and strongly weathered zone. The weathering crust belongs to sialferit, characterized with high Si-Al-Fe oxide contents (88.0-91.0 wt.%). Mineral compositions of altered layers mainly consist of illite, kaolinite, quartz, feldspar, chlorite and goethite.

2. Chemical weathering indices that could be effectively applied to evaluate weathering grade of the Dai Loc granitoids include R, WIP, STI, Wp, CIW, CIA and I_{mob}. Among them, R, WIP, STI and Wp increase, whereas CIW, CIA and I_{mob} decrease from top layers to saprolite and fresh rock layers, corresponding to a progressively weak weathering grade towards the beneath. Similarly, N_q and X_d values obviously tends to rise from the saprolite (0.79 and 0.66, respectively, VL10-L4) to the top layer (0.94 and 0.89, respectively).

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