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Research paper

A preliminary study on the new geotechnical weathering index in the evaluation of altered biotite granite

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Abstract

The existing chemical index of alteration has a difficulty to evaluate the degree of weathering in biotite granites due to an assumption that K_2O content decreases along with Na_2O, CaO, and MgO. We found that relative K_2O content increases during weathering of biotite granite, as it is retained within such rocks due to (1) the chemical and physical stability of K-feldspar and (2) the formation of illite via incorporation of K ions released from biotite. The calculated ranges of most chemical indexes for biotite granite weathering do not show a good correlation with the weathering grade except the CIW, WIP and V indexes. The range of the CIW, WIP and V indexes according to the weathering grade were very small, and thus small errors in whole-rock chemical analyses can produce large discrepancies in calculated values. Further, the WPI index is a relative weathering index that depends on the composition of a fresh standard sample and cannot be applied to determine the absolute degree of weathering in granites if no protolith is available. We suggest a new weathering index (BWI; Biotite weathering index) based on a decrease in the number of K ions in the interlayer site of biotite during weathering of granite. Newly calculated values show a much wider range than the CIW, WIP and V indexes with a good relationship with a weathering grade. Therefore, it is necessary to establish the new index for a detailed classification of weathering degree.

Keywords: *Biotite weathering index (BWI); Biotite; Granite; Weathering.*

1. Introduction

Most rocks on the Earth's surface are exposed to weathering processes. Plutonic igneous rocks formed at great depths are initially composed of crystalline minerals that are unstable at surface pressures and temperatures, which readily weather to secondary, more stable minerals such as clays. The proportion of secondary minerals within an igneous rock increases proportionally with the degree of weathering; however, as secondary minerals are significantly weaker than primary crystalline minerals, civil engineering projects undertaken on highly weathered rocks are extremely hazardous [1–5]. As such, quantification of the degree of weathering is critical in order to evaluate ground stability before infrastructure development [4,5]. Several chemical weathering studies have been performed over the last century to measure the extent to which a rock is weathered [6–14]. For example, Nesbitt and Young [10] and Harnois [11] developed the Chemical Index of Alteration (CIA) and Chemical Index of Weathering (CIW), respectively, which are based on changes in whole-rock chemical compositions under the assumption that these changes are similar for all rock types. However, it was found that the chemical weathering indices based on whole rock geochemistry have difficulty in accurately evaluating the degree of weathering as they only consider whole-rock chemistry, and not complex weathering processes such as *in-situ* mineral dissolution and precipitation [5, 15]. The inaccuracy of these indices may be related to different weathering processes occurring in different lithologies, which result in distinct bulk-rock compositional changes during weathering. For example, sedimentary rocks weather differently compared to igneous rocks owing to varying mineral constituents in each rock type. Moreover, common weathering processes in volcanic and plutonic igneous rocks widely vary, as the former mostly consist of glass, whereas the latter mostly contain crystalline minerals. Previously proposed weathering indices have not considered that different weathering processes generally occur in different types of rocks; consequently, some are very good for particular examples, but not for others, and it is unclear as to which indices are best suited to which lithologies. Thus, weathering indices based solely on a generic (and simplified) weathering process—without necessarily accounting for variation in bulk-rock compositions—should be replaced by a more accurate weathering indices.

One way to implement an improved weathering index is to consider individual mineral chemistry instead of whole-rock chemistry, as the compositional changes that occur in certain minerals during weathering are likely to be mostly independent of bulk-rock composition. Biotite is one possible index mineral that can be used in such an evaluation, as it shows clear compositional changes during alteration [16, 17]. Biotite commonly alters to vermiculite and chlorite in the early stages of weathering [18–21], forming mixed (or intergrown) biotite/vermiculite (B/V) and biotite/chlorite (B/C) phases [22–24]. Continued weathering causes kaolinite and goethite to completely replace these mixed phases [23, 25–27]. The alteration of biotite during this weathering process progressively leaches K ions from its interlayer sites.

In this work, we introduce a new weathering index that focuses on changes in biotite composition. Granitic samples that have undergone three different degrees of weathering have been analyzed in terms of their whole-rock chemical compositions and the compositions of constituent minerals. Based on these data, we have investigated the amount of leached K from biotite in during progressive weathering. We have formulated a new Biotite-weathering index (BWI) and have evaluated its ability to measure the extent of weathering in biotite granite compared to three other well-established weathering indices (CIA, CIW, and WIP). Our results show that the BWI can provide more accurate information about the degree of weathering in biotite granite than these current alternatives.

2. Methods

For this study, drill-core samples of biotite granite were obtained from the Daejeon area, South Korea. Seven cores were classified into four types according to the degree of weathering exhibited (i.e., fresh, weakly, moderately, and strongly weathered granites). The degree of weathering was determined via field definition suggested by ISRM [28] together with optical microscopy according to the degree of alteration of key minerals such as biotite and plagioclase. The fresh, weakly, moderately, and strongly weathered granites can be matched to very strong (R5), strong (R4), medium strong (R3) and weak strong rocks (R2) in ISRM [28] simple field classification. Representative samples for fresh, moderately and strongly weathered granites are termed WS (weathering stage) 1, 2, and 3, respectively in this paper (Fig. 1). WS1 granite core was left outdoors in order for it to weather between June 2011 and June 2012, and its extent of alteration was investigated after six months and one year. During outdoor experiment, the average temperature was 14.4°C and the average rainfall was 7.6mm/day. The samples were located within plastic boxes without drainage hole and water was removed by evaporation. The granite samples that had weathered for six months and one year are referred to herein as WS1-1 and WS1-2, respectively. WS-1-1 and WS-1-2 are changed into weakly and moderately weathered granites during experiment. Bulk-rock chemistry of the three representative granites (WS1, WS2, and WS3) and two experimental granites (WS1-1 and WS1-2) were analyzed using X-ray fluorescence (XRF), and the chemical compositions of minerals in those granites were analyzed by electron probe microanalysis (EPMA). Observation via a transmission electron microscope (TEM) was conducted on biotite in the strongly weathered granite (WS3) in order to determine its alteration state at the strongly weathered stage. The average composition of minerals in each granite type was obtained by averaging analyses of twenty of each weathered mineral. XRF analyses were performed at a voltage of 24–40 kV and a current of 50–80 mA using a PW2400 XRF (Philips) housed at the Korea Basic Science Institute (Daegu center), Korea. EPMA and TEM analyses were performed using a Shimadzu 1600 and JEM-2200FS housed at the Korea Basic Science Institute (Jeonju center), Korea. EPMA analysis operating conditions were 15 kV and 20 mA, and TEM observations were performed at 200 kV.

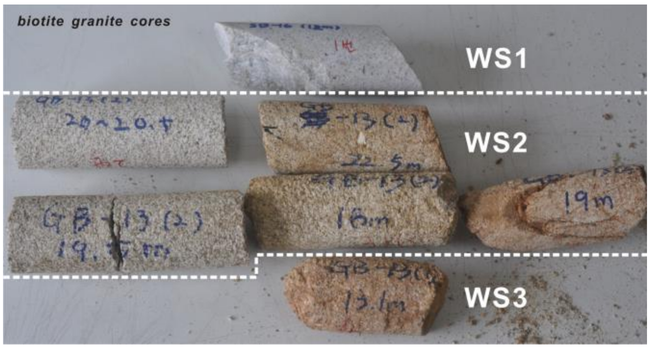

Fig. 1: Photograph of biotite granite cores obtained from the Daejeon area. WS1, WS2, and WS3 represent weakly, moderately, and strongly weathered granites, respectively. Samples 1, 2, and 3 were analyzed in this study.

In order to compare the weathering index and geotechnical properties of the granite samples, the dry density, absorption rate, and uniaxial compressive strength were measured. Statistical methods were used to evaluate the reliability of the data and the correlation with the weathering indices proposed in previous studies. The program used for the analysis was PASW statistics.

3. Results

3.1. Whole-rock chemistry

The results of whole-rock geochemical analysis of each granite core are presented in Table 1. The main changes recorded during weathering occur for Na_2O, CaO, K_2O, and MgO contents (Table 1). Bulk-rock K_2O content increased during weathering, although Na_2O, CaO, and MgO contents decreased, with the magnitude of change in CaO content being particularly noticeable. Decreasing Na_2O and CaO contents are well-documented results of weathering processes that occur in igneous rocks [29].

Table 1: Whole-rock Chemistry of the Granite Cores That Have Been Weathered to Different Degrees and the Calculated Weathering Indices for Each Granite. L.O.I. = loss on ignition

	WS1	WS1-1 after six months	WS1-2 after one year	WS2	WS3
	Fresh	Slightly weathered	Moderately weathered	Moderately weathered	Strongly weathered
SiO_2	72.93	71.52	74.01	72.72	73.08
Al_2O_3	15.19	15.59	14.75	14.82	14.74
TiO_2	0.10	0.14	0.08	0.26	0.24
Fe_2O_3	0.99	1.69	0.95	1.10	1.10
MnO	0.03	0.07	0.02	0.02	0.02
MgO	0.37	0.63	0.24	0.20	0.18
CaO	1.20	1.20	1.18	0.76	0.26
Na_2O	3.70	3.43	3.18	3.54	3.48
K_2O	3.20	3.25	3.64	5.11	5.42
P_2O_5	0.08	0.08	0.08	0.06	0.06
L.O.I.	2.13	1.68	1.68	1.25	1.20
Total	99.91	99.79	99.82	99.84	99.78
CIA	**56.83**	**58.30**	**57.00**	**54.06**	**55.29**
CIW	65.28	67.13	67.24	67.73	70.89
CWI	2.77	2.70	2.71	2.64	2.63
WIP	0.00	5.41	10.88	12.00	23.46
BWI	18.50	32.00	52.00	53.00	100.00
PI	88.66	87.92	89.10	88.83	88.93
SAR	8.15	7.78	8.51	8.33	8.41
V	2.03	2.03	2.34	2.64	3.10
Si-Ti index	88.41	87.73	88.94	87.53	87.75
WPI	4.96	5.86	5.13	6.70	6.31
Strength (MPa)	123.00	39.00	-	27.00	17.50

CIA: $[Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)]\times100$ [10]
CIW: $[Al_2O_3/(Al_2O_3+CaO+Na_2O)]\times100$ [11]
CWI: $[Al_2O_3+Fe_2O_3+TiO_2]/[Al_2O_3+CaO+Fe_2O_3+K_2O+MgO+MnO+Na_2O+P_2O_5+SiO_2+TiO_2]\times100$ [30]
WIP : $[(CaO+Na_2O)_{\text{fresh rock}}-(CaO+Na_2O)_{\text{sample}}]]\times100/(CaO+Na_2O)_{\text{fresh rock}}$ [27]
PI: $[SiO_2/(Al_2O_3+Fe_2O_3+SiO_2)]\times100$ [8]
SAR: SiO_2/Al_2O_3 [7]
V: $(Al_2O_3+K_2O)/(MgO+CaO+Na_2O)$ [6]
Si Ti Index: $[(SiO2/TiO_2)/((SiO_2/Al_2O_3)+(SiO_2/TiO_2))]\times100$ [31]
WPI: $[(K_2O+Na_2O+CaO+MgO-L.O.I)/(SiO_2+Al_2O_3+TiO_2+Fe_2O_3+CaO+MgO+Na_2O+K_2O)]\times100$ [32]

The weathering indexes CIA, CIW, and WIP, CWI, Pl, SA, SiTi, WPI and MWPI were calculated for the variously weathered granite cores based on their whole-rock chemistry (Table 1). Calculated CIW, WIP and V values increased as the weathering degree increased from WS1 to WS3, which is expected, as these indices were originally proposed under the assumption that Na_2O and CaO are released from rocks during weathering. However, values for the CIA decreased during the weathering process from WS1 to WS3, though clearly they should have increased (Table 1). This discrepancy is likely due to the CIA assumption that Na_2O, K_2O, CaO, and MgO contents decrease due to their removal from rocks during weathering [10]; however, the relative bulk-rock K_2O content was seen to have increased during weathering in our study (Table 1). The relative increase in K_2O content occurred due to the resistance of K-feldspar (one of the main sources of K) to weathering, as it is less susceptible than plagioclase (the main source of Na and Ca). Further, K_2O released from biotite during weathering, which is another source of K, remained *in-situ* because it was used to form the secondary mineral illite, instead of being leached from the rocks. The resistance of K-feldspar and the formation of illite can be easily identified via optical microscopy, as documented below. Therefore, the CIA, which assumes that bulk-rock K_2O contents decrease during alteration [10], cannot accurately measure the degree of weathering of these granite cores. Other weathering indexes also do not show systematic increase as WIP, CIW and V (Table 2). Progressive weathering from WS1 to WS3 through WS1-1, WS1-2 and WS-2 was thus documented by the CIW and WIP, but not by the CIA and other indexes.

Table 2: Average Compositions of Minerals in the Granite Cores

	WS1			WS2			WS3		
	Biotite	Illite	Plagioclase	Biotite	Illite	Plagioclase	Illite	Kaolinite	Plagioclase
SiO_2	31.888	49.714	61.500	31.521	47.765	65.152	46.998	43.559	67.668
Al_2O_3	18.803	31.326	23.108	16.825	29.477	20.542	31.090	35.894	20.326
FeO	23.904	2.995	0.018	26.843	4.940	0.000	4.045	3.084	0.014
CaO	0.004	0.022	3.659	0.283	0.115	0.671	0.003	0.106	0.259
MgO	6.282	1.895	0.010	5.394	1.863	0.000	1.391	0.395	0.001
Na_2O	0.043	0.087	8.545	0.151	0.114	9.498	0.103	0.052	9.483
K_2O	7.816	8.398	0.203	4.380	6.936	0.099	8.903	0.383	0.058
TiO_2	1.919	0.285	0.005	1.019	0.478	0.000	0.155	0.010	0.004
MnO	0.611	0.043	0.008	0.141	0.019	0.000	0.022	0.017	0.006
Total	91.271	94.763	97.055	86.571	91.706	95.962	92.710	83.500	97.819
Si	5.20	6.58	2.79	5.40	6.57	2.95	6.44	3.95	2.99
Al	3.62	4.90	1.24	3.40	4.77	1.10	5.02	3.84	1.06
Fe	3.26	0.33	0.00	3.88	0.58	0.00	0.47	0.24	0.00
Ca	0.00	0.00	0.18	0.05	0.02	0.03	0.00	0.01	0.01
Mg	1.53	0.37	0.00	1.38	0.38	0.00	0.28	0.05	0.00
Na	0.01	0.02	0.75	0.05	0.03	0.83	0.03	0.01	0.81
K	1.63	1.42	0.01	0.94	1.21	0.01	1.56	0.04	0.00
Ti	0.24	0.03	0.00	0.13	0.05	0.00	0.02	0.00	0.00
Mn	0.08	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00

3.2. Results of microscopic observation and EPMA analysis

The WS1 core consisted of biotite, quartz, plagioclase, and K-feldspar (Figs 2a, b), with biotite observed during EPMA analysis to be slightly weathered (Figs 3a, b). Two distinct domains occurred within these weathered grains (Fig. 3b): a bright area of slightly weathered biotite and a dark area of illite that formed due to weathering. Figure 3b shows that part of biotite was also altered to chlorite. The average measured chemical composition of weathered biotite (Table 2) was $K_{1.63}(Fe_{3.26}Mg_{1.53}Ti_{0.24}Mn_{0.08}Al_{0.82})(Si_{5.20}Al_{2.80})O_{20}(OH)_4$, indicating that the interlayer K cation proportion (K=1.63) was lower than that of an ideal biotite (K=2.00). This result implies that biotite was mixed with chlorite, which has no interlayer K cation; however, it was difficult to differentiate between biotite and chlorite via optical microscopy and EPMA analyses as both were intergrown at a scale smaller than the EPMA resolution limit. The analyzed illite had an average composition of $K_{1.42}(Al_{3.48}Fe_{0.33}Mg_{0.37})(Si_{6.58}Al_{1.42})O_{20}(OH)_4$ (Table 2), which is within the range of an ideal analysis reported by Deer et al. [33].

In this sample, plagioclase also exhibited slight weathering, although K-feldspar was almost completely fresh and lacked any significant alteration (Figs 2a, b). The average formula of the weathered plagioclase was $(Na_{0.75}Ca_{0.18})Al_{1.03}(Si_{2.79}Al_{0.21})O_8$ (Table 2).

Biotite and plagioclase in WS2 were more extensively altered than grains in WS1 (Figs 2c, d), with those grains in the former having more dirty surfaces covered with secondary minerals than those in the latter. Backscattered electron (BSE) images of biotite in WS2 showed significantly more dark regions than for WS1, indicating that the biotite in WS2 had been more strongly altered to illite than those in WS1 (Fig. 3c). Analyzed average formulae of weathered biotite and illite in WS2 core were $K_{0.94}(Fe_{3.88}Mg_{1.38}Ti_{0.13}Mn_{0.02}Al_{0.80})(Si_{5.40}Al_{2.60})$ $O_{20}(OH)_4$ and $K_{1.21}(Al_{3.34}Fe_{0.58}Mg_{0.38})(Si_{6.57}Al_{1.43})O_{20}(OH)_4$, respectively (Table 2). The proportion of K in WS2 biotite was thus significantly reduced in comparison to that in WS1. The illite in WS2 also contained less K and slightly more Fe than the illite in WS1. Although chlorite was not observed in BSE images (Fig. 3c), the low K content and slight increase in Fe content in illite suggested that chlorite may have existed as a microscopic mixed phase within the illite, and therefore could not have been directly observed during EPMA analysis.

The average formula of the weathered plagioclase in WS2 core was $(Na_{0.83}Ca_{0.03})Al_{1.05}(Si_{2.95}Al_{0.05})O_8$ (Table 2). A comparison of plagioclase compositions in WS2 and WS1 showed that their Na and Ca ions were removed during continued weathering. In contrast, the K-feldspar in WS2 was still fresh, similar to grains observed in WS1, indicating that it is notably more resistant to weathering than biotite and plagioclase (Figs 2c, d).

Biotite in WS3 core had been completely consumed due to strong alteration, leaving behind biotite pseudomorphs. Additionally, plagioclase in WS3 was more extensively altered than in WS2 (Figs 2e, f). Biotite pseudomorphs were composed of three secondary minerals that had different contrasts in BSE imagery: illite, kaolinite, and goethite (Fig. 3d). TEM analysis and energy-dispersive spectroscopy (EDS) showed that illite and goethite had replaced biotite (Fig. 5). Our observed breakdown of biotite into the secondary minerals kaolinite and goethite (with minor illite) in the strongly weathered core has also been documented in previous works [23, 25–27, 34]. The average formula of illite in WS3 core was $K_{1.56}(Al_{3.46}Fe_{0.47}Mg_{0.28})(Si_{6.44}Al_{1.56})O_{20}(OH)_4$ (Table 2), which had a higher K content than grains analyzed in WS1 and WS2 (Table 2). This high K content may have been caused by an increased amount of K made available to illite during the complete breakdown of biotite in this strongly weathered stage, and/or by alteration of a portion of illite to kaolinite. No chlorite was observed in WS3, suggesting that all previous grains (if present) may have broken down to goethite.

Plagioclase in strongly altered WS3 core exhibited dusty surfaces, which were extensively replaced by fine-grained secondary minerals (Figs 2e, f). The average composition of weathered plagioclase was $(Na_{0.81}Ca_{0.01})Al_{1.05}(Si_{2.99}Al_{0.01})O_8$ (Table 2). Even at this stage, K-feldspar was still fresh, further indicating its relative stability during weathering compared to biotite and plagioclase (Figs 2e, f).

Under the microscope, WS1-1 and WS1-2 showed only minor differences in their degree of weathering compared to WS1 core (Figs 2e and 2f); however, a there was systematic decrease in K ions in biotite from WS1 to WS1-1, and from WS1-1 to WS1-2 (Tables 2 and 3). The average formulae of biotite in WS1-1 and WS1-2 were $K_{1.36}(Fe_{3.36}Mg_{1.42}Ti_{0.19}Mn_{0.08}Al_{0.95})(Si_{5.31}Al_{2.69})O_{20}(OH)_4$ and $K_{0.96}(Fe_{3.53}Mg_{1.35}Ti_{0.33}Mn_{0.06}Al_{0.92})(Si_{5.04}Al_{2.96})O_{20}(OH)_4$, respectively. The K content of biotite in WS1-1 was between those measured in grains from WS1 and WS2, and its content in WS1-2 was similar to that for grains in the WS2 granite (Table 3). Therefore, it appeared that the WS1 granite core had been weathered to a similar degree as WS2 by the exposure to the environment for only one year. Biotite in WS1-1 and WS1-2 was partially altered to illite, with the illite average formulae in both samples being $K_{1.29}(Al_{3.22}Fe_{0.52}Mg_{0.49})(Si_{6.58}Al_{1.42})O_{20}(OH)_4$ and $K_{1.48}(Al_{3.15}Fe_{0.73}Mg_{0.46})(Si_{6.20}Al_{1.80})O_{20}(OH)_4$, respectively.

Table 3: Average Compositions of Biotite, Illite, and Plagioclase in the WS1-1 and WS1-2 Granite Cores

	WS1-1 (after six months)			WS1-2 (after one year)		
	Biotite	Illite	Plagioclase	Biotite	Illite	Plagioclase
SiO_2	32.742	47.290	61.725	30.628	44.451	64.958
Al_2O_3	19.018	28.815	24.084	19.969	30.097	21.012
FeO	24.683	3.916	0.023	25.430	5.999	0.072
CaO	0.004	0.237	5.166	0.059	0.079	1.755
MgO	5.887	2.261	0.003	5.489	2.137	0.013
Na_2O	0.042	0.053	8.734	0.067	0.225	10.946
K_2O	6.618	7.348	0.170	4.649	8.347	0.129
TiO_2	1.551	0.697	0.000	2.721	0.918	0.004
MnO	0.584	0.133	0.007	0.411	0.089	0.009
Total	91.130	90.750	99.912	89.424	92.342	98.897
Si	5.31	6.58	2.74	5.04	6.20	2.89
Al	3.64	4.64	1.26	3.88	4.95	1.10
Fe	3.36	0.52	0.00	3.53	0.73	0.00
Ca	0.00	0.03	0.25	0.01	0.01	0.08
Mg	1.42	0.49	0.00	1.35	0.46	0.00
Na	0.01	0.02	0.75	0.02	0.06	0.94
K	1.36	1.29	0.01	0.96	1.48	0.01
Ti	0.19	0.09	0.00	0.33	0.10	0.00
Mn	0.08	0.02	0.00	0.06	0.01	0.00

Plagioclase in WS1-1 and WS1-2 showed more microscopic evidence of alteration compared to grains in WS1 (Fig. 4), with grains in WS1-2 exhibiting a similar degree of alteration to those in WS2. The average analyzed formulae of plagioclase in WS1-1 and WS1-2 were $(Na_{0.75}Ca_{0.25})Al_{1.00}(Si_{2.74}Al_{0.26})O_8$ and $(Na_{0.94}Ca_{0.08})Al_{0.99}(Si_{2.89}Al_{0.11})O_8$, respectively (Table 3). The K-feldspar in WS1-1 and WS1-2 was also still as fresh as those grains observed in WS1 (Figs 2a, b).

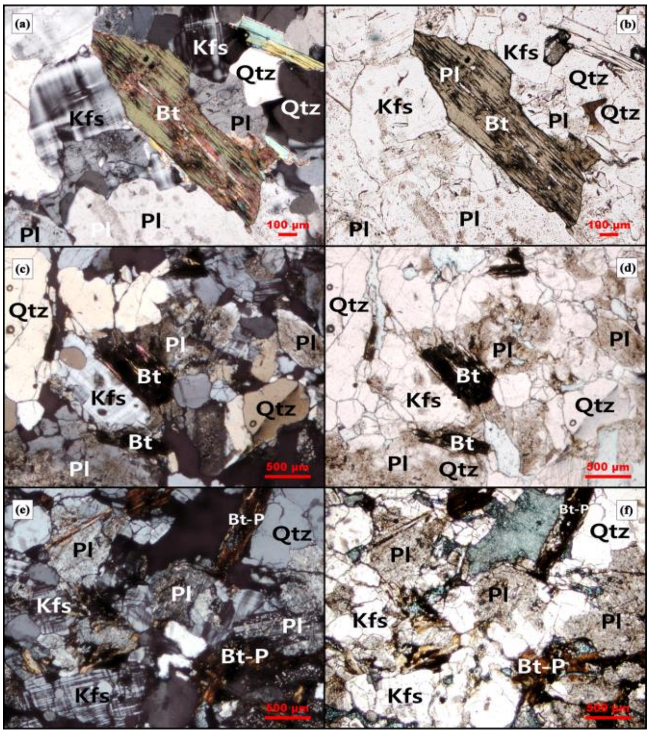

Fig. 2: Photomicrographs of (a, b) WS1 granite cores, (c, d) WS2 granite cores, and (e, f) WS3 granite cores. Photomicrographs (a), (c), and (e) were taken under cross-polarized light, and (b), (d), and (f) were taken under plane-polarized light. Qtz: Quartz, Bt: Biotite, Pl: Plagioclase, Kfs: K-feldspar, and Bt-P: Biotite pseudomorph.

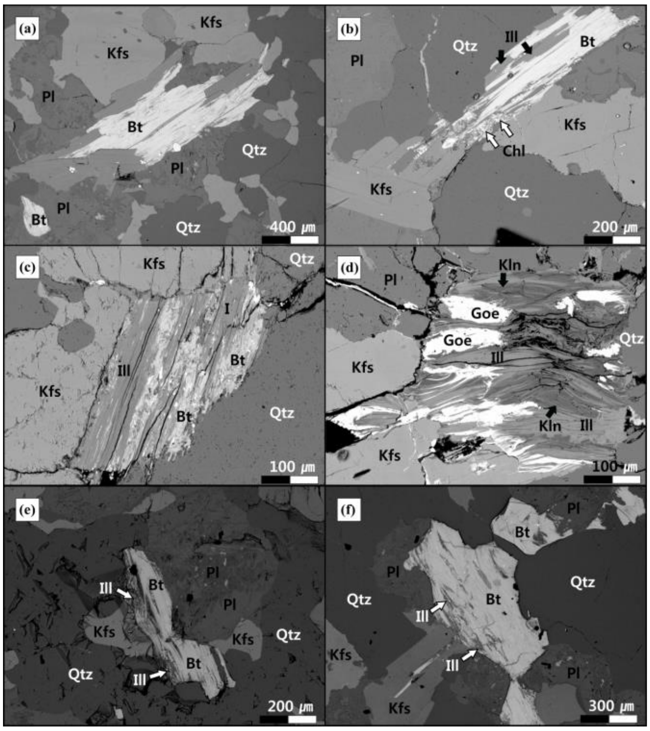

Fig. 3: BSE images of (a, b) WS1, (c) WS2, (d) WS3, (e) WS1-1, and (f) WS1-2. The same abbreviations are used here as in Fig. 2, in addition to Ill: Illite, Chl: Chlorite, Kln: Kaolinite, and Goe: Goethite.

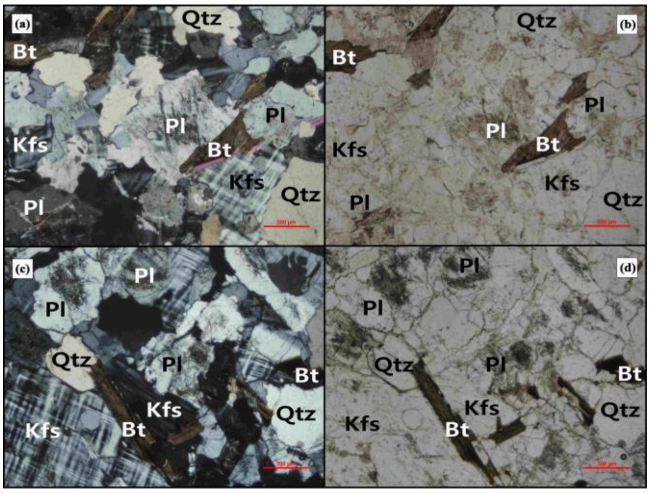

Fig. 4: Photomicrographs of (a, b) WS1-1 and (c, d) WS1-2. Photomicrographs (a) and (c) were taken under cross-polarized light, and (b) and (d) were taken under plane-polarized light. Abbreviations are the same as those used in Fig. 2.

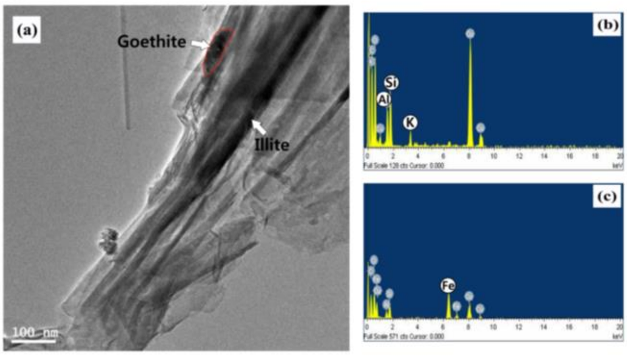

Fig. 5: (a) TEM image of illite and goethite replacement of weathered biotite in WS3. EDS results indicating (b) illite and (c) goethite.

3.3. BWI weathering index and Compressive strength

In this paper, we introduce the Biotite-weathering index (BWI), which can measure the degree to which granite has weathered more precisely than any other chemical weathering indices. The BWI is based on the decrease in the quantity of K ions in biotite's interlayer site that occurs during weathering. In general, biotite in slightly weathered granite is partially altered to secondary minerals such as chlorite, vermiculite, and illite, and is completely replaced by kaolinite and goethite in extremely weathered samples [22, 24, 27, 34–37]. As shown herein, biotite can survive the early stages of weathering in granite, though does not remain in very strongly weathered granite. The proportion of K in biotite decreased as weathering became more extreme, such that the degree of weathering can be quantified using the ratio of K in weathered biotite and that in the ideal biotite formula (i.e., 2 ions). The BWI formula is thus as follows:

$$\text{BWI} = 100 - [(\text{Value of K in weathered biotite}) / (\text{Value of K in ideal biotite formula}) \times 100] \qquad (1)$$

The BWI was calculated for WS1, WS1-1, WS1-2, WS2, and WS3 using compositional analyses of biotite obtained herein (Table 1). The BWI values for WS1 and WS2 were 18.5 and 53, respectively (Table 1), and was 100 for WS3, given that the value of K in that latter case was 0 owing to its complete alteration to illite, kaolinite, and goethite (Fig. 3d). Calculated BWI values for WS1-1 and WS1-2 were 32 and 52, respectively. The BWI value for WS1-2 was similar to that for WS2, indicating that one-year of exposure to the natural environment was sufficient to convert the extent of weathering in WS1 to a degree similar to that observed in WS2.

The compressive strength obtained from WS1, WS1-1, WS-2 and WS-3 are 123, 39, 27 and 17.5 Mpa, respectively. In the simple regression analysis on the correlation between the BWI weathering index and compressive strength, the coefficient of determination (R^2) was 0.9113 representing very high correlation between them and the following equation was obtained (Fig. 6). More study will be needed to confirm the suggested equation.

$$\text{Rock strength (MPa)} = 2456.9 \times (\text{BWI})^{-1.109} \quad (2)$$

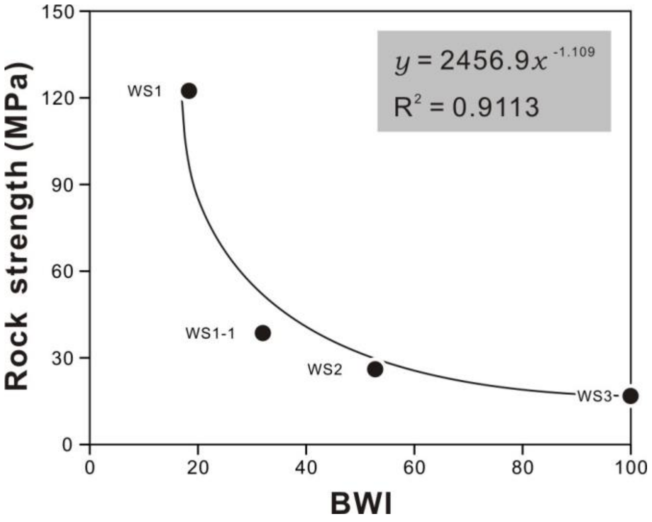

Fig. 6: The correlation between BWI and Rock Strength (MPa) which were measured from rocks with different weathering degree.

4. Discussion and conclusions

The chemical weathering indices based on whole rock composition have been used as an important tool for evaluating weathering condition in ground investigation practice. However they were recently criticized due to their inaccuracy because the whole rock composition depends not only on the degree of weathering but also on microenvironmental conditions that control the type and abundance of weathering minerals [15]. Price and Velbel [38] also mentioned that CIA, CIW, Plagioclase Index of Alteration (PIA) and Vogt's Residual Index (V) may have problem for evaluating weathering degree because they are sensitive to subtle geochemical changes such as hydrothermal alteration.

This study also confirmed the problems of a chemical weathering indices based on the whole rock compositions. The CIA [10] fails to properly evaluate the weathering degree of biotite granites, and that the CIW [11] and WIP [27] provide better metrics compared to other weathering indexes (Table 1), though still have some drawbacks. The CIA suffers from the assumption that K_2O decreases commensurately with Na_2O, CaO, and MgO during weathering; however, relative K_2O content was observed to increase in our samples during the weathering process, with it remaining *in-situ* due to the strong resistance of K-feldspar against weathering and the formation of illite that scavenged K ions released from biotite during its breakdown. Therefore, the CIA cannot be used to determine the weathering degrees of granitic rocks that have abundant K-feldspar and biotite. Because the CIW assumes that Na_2O and CaO decrease during the weathering process, this index has previously been considered useful for quantifying weathering in granitic rocks [38–40], which is supported by the results of this study (Table 1), although the observed magnitude of change herein was very narrow, ranging from 65.28 (WS1, weakly weathered granite) to 70.89 (WS3, strongly weathered granite). Therefore, only a small error in the whole-rock chemical analysis could strongly influence the weathering evaluation, and obtaining detailed and reliable geochemical analyses of weathered rocks is difficult. In this study, the CIW values for WS1-1 and WS1-2 were very similar, thus confirming this issue (Table 1). Similar problem occurs for the V values (Table 1). Although the WIP [27] for our samples exhibited a wide range from 0.00 (WS1, weakly weathered granite) to 23.46 (WS3, strongly weathered granite), it is a relative weathering index that depends on the composition of a standard fresh sample. Therefore, the WIP cannot be used to determine the absolute extent to which granite has been weathered. Consequently, it is necessary to develop a new weathering index that is only controlled by the degree of weathering.

The correlation among weathering indexes including BWI was evaluated statistically and the result was shown in Fig. 7 and Table 4.

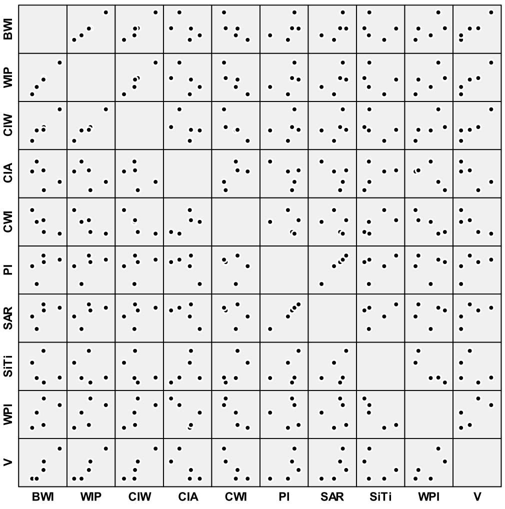

Fig. 7: The matrix plot of values calculated from the rocks with different weathering degree using various weathering indexes including BWI.

Table 4: Correlation Coefficient Matrix and Correlation Analysis of Weathering Indices

		BWI	WIP	CIW	CIA	CWI	PI	SAR	SiTi	WPI	V
BWI	Pearson correlation coefficient	1	.995**	.975**	-.534	-.824	.495	.576	-.282	.567	.960**
	p-value (2 side test)		.000	.005	.354	.086	.396	.309	.646	.319	.010
	N	5	5	5	5	5	5	5	5	5	5
WIP	Pearson correlation coefficient	.995**	1	.976**	-.555	-.870	.481	.570	-.314	.621	.958*
	p-value (2 side test)	.000		.005	.332	.055	.412	.316	.607	.264	.010
	N	5	5	5	5	5	5	5	5	5	5
CIW	Pearson correlation coefficient	.975**	.976**	1	-.451	-.865	.293	.358	-.432	.652	.917*
	p-value (2 side test)	.005	.005		.446	.058	.632	.522	.468	.233	.028
	N	5	5	5	5	5	5	5	5	5	5
CIA	Pearson correlation coefficient	-.534	-.555	-.451	1	.664	-.606	-.610	.425	-.678	-.746
	p-value (2 side test)	.354	.332	.446		.221	.279	.274	.476	.209	.148

	N	5	5	5	5	5	5	5	5	5	5
CWI	Pearson correlation coefficient	-.824	-.870	-.865	.664	1	-.223	-.322	-.652	-.914*	-.857
	p-value (2 side test)	.086	.055	.058	.221		.718	.597	.233	.030	.064
	N	5	5	5	5	5	5	5	5	5	5
PI	Pearson correlation coefficient	.495	.481	.293	-.606	-.223	1	.991**	.423	-.035	.570
	p-value (2 side test)	.396	.412	.632	.279	.718		.001	.478	.956	.316
	N	5	5	5	5	5	5	5	5	5	5
SAR	Pearson correlation coefficient	.576	.570	.385	-.620	-.322	.991**	1	.382	.040	.631
	p-value (2 side test)	.309	.316	.522	.274	.597	.001		.526	.949	.253
	N	5	5	5	5	5	5	5	5	5	5
SiTi	Pearson correlation coefficient	.282	-.314	-.432	.425	-.652	.423	.382	1	-.876	-.381
	p-value (2 side test)	.646	.607	.468	.476	.233	.478	.526		.051	.527
	N	5	5	5	5	5	5	5	5	5	5
WPI	Pearson correlation coefficient	.567	.621	.652	-.678	-.914*	-.035	.040	-.876	1	.668
	p-value (2 side test)	.319	.264	.233	.209	.030	.956	.949	.051		.218
	N	5	5	5	5	5	5	5	5	5	5
V	Pearson correlation coefficient	.960**	.958*	.917*	-.746	-.857	.570	.631	-.381	.668	1
	p-value (2 side test)	.010	.010	.028	.148	.064	.316	.253	.527	.218	
	N	5	5	5	5	5	5	5	5	5	5

(*): The correlation coefficient is significant at the 0.05 level.

(**): The correlation coefficient is significant at the 0.01 level.

The result indicates that the BWI was strongly correlated with the CIW, WIP and V, demonstrating its validity as a weathering index. The range of BWI values (18.5–100) for the biotite granite studied herein was much wider than the calculated ranges of the CIW (65.28–70.89), WIP (0.00–23.46) and V(2.03-3.10) (Fig. 8). Therefore, a detailed classification of weathering degree, which is difficult to obtain with the CIW, WIP and V, can be achieved with the BWI (Fig. 8). Though the WIP only provides a relative measure of weathering-related change, as it utilizes the composition of a fresh standard, the BWI does not suffer from this limitation, as it does not require use of an unaltered sample. In addition, the BWI may be applied to a wide range of rock types in addition to granite, because biotite is a common mineral in many igneous and metamorphic lithologies. All the more, the BWI index showed a good correlation with the compressive strength suggesting possibility that the BWI can be used for indirectly estimating compressive strength (Fig. 6).

We conclude that the BWI, which considers K ion contents in biotite to elucidate the degree of weathering that a rock has experienced, can obviate the problems associated with other weathering indices, such as the CIA, CIW, and WIP. It is necessary to apply the BWI to more samples of granite that have been variably weathered in order to reconfirm the relationship between the BWI and the weathering degree. It is also necessary to investigate the relationships between BWI and the physical strength of granite including compressive strength, and to confirm whether the BWI can be used to evaluate the degree of weathering in other biotite-bearing lithologies. We expect that further study of the BWI will enable development of a simple and accurate method for determining the extent of weathering in a wide range of biotite-bearing igneous and metamorphic rocks.

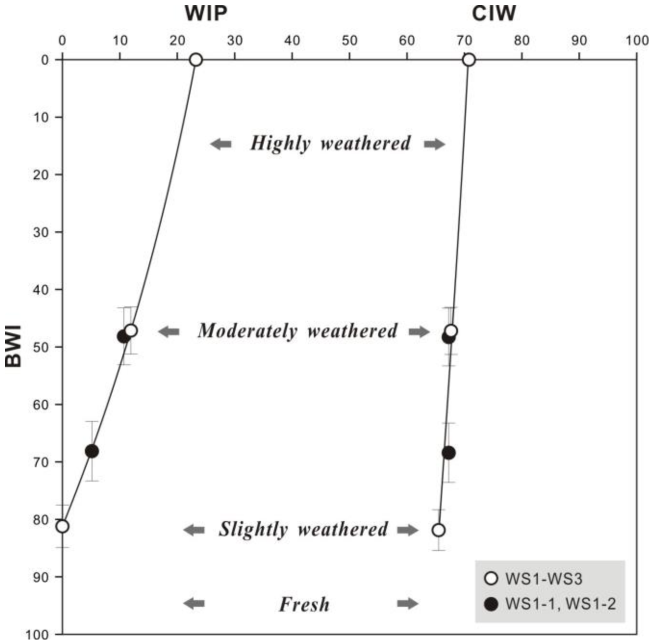

Fig. 8: Relationships between BWI values and those of two other weathering indices (CIW and WIP) for biotite granites that have been weathered to different degrees. The rectangles and bars represent the averages and ranges, respectively, of BWI for biotites from biotite granites that have been weathered to different degrees

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