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Chemical Weathering Rates and Mineralogical Characteristics of Soils Developed on Tuff from Semilir Formation

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ABSTRACT: The Semilir Formation is part of the southern mountainous zone south of central Java. This formation consists of tuff, lapily tuff, lapily pumice, pumice breccia, and shale. The thickness of this formation is more than 460 meters. Studies on the chemical and mineralogical properties of soil derived from the weathering of tuff rocks in the Semilir Formation have never been carried out. Twelve soil samples from different areas within the Semilir Formation were analyzed for their chemical and mineral properties. X-ray fluorescence (XRF) and X-ray diffraction (XRD) techniques were used for chemical and mineralogical analysis. The results of the XRF test will be used to calculate an efficient chemical weathering indices to assess the development of soil from the underlying rock. The XRD test results indicate that the dominant mineral contents in the samples are calcite, anorthite, quartz, mica, metahalloysite, and saponite. The chemical composition results show that the SiO_2, Al_2O_3, and Fe_2O_3 content in the residual tuff soil increases with the degree of weathering while CaO decreases. Furthermore, MgO, Na_2O, K_2O, and TiO_2 do not report a good correlation with the degree of weathering. This study demonstrated that, among the evaluated weathering indices, the Weathering Index of Parker (WIP), the Chemical Index of Alteration (CIA), the Chemical Weathering Index (CIW), and the Plagioclase Alteration Index (PIA) were the most proper indices for predicting tuff weathering intensity. CIW and CIA show very good correlations since CIW is a modified chemical weathering index from CIA; hence, the calculation of both indices shows similar results. WIP and CIA, WIP and CIW, and WIP and PIA also show good correlations.

KEYWORDS: Chemichal Weathering Indices, Degree of Weathering, Mineralogy, Soil, Tropical, and Tuff.

1. INTRODUCTION

The Semilir Formation is part of the southern mountainous zone south of central Java, Indonesia. This formation was developed from the eruption of an ancient volcano, Mount Semilir, located south of Klaten. The lithology consists of tuff, lapily tuff, lapily pumice, pumice breccia, and shale. The tuff and claystone within the formation show a range in composition from andesite to dacite. The Semilir Formation shows a lateral distribution that stretches from the west of the Southern Mountains, in the Pleret-Imogiri area, to the west of Mount Sudimoro, Piyungan-Prambanan, in the middle of Mount Baturagung and its surroundings, to the east on the heights of Mount Gajahmungkur, Wonogiri. The thickness of this formation is more than 460 meters (Surono, Toha and Sudarno, 1992; Rahardjo, Sukandarrumidi and Rosidi, 1995; Sampurno and Samodra, 1997).

Weathering is the change and decomposition of rocks at or near the earth's surface due to physical, chemical, and biotic influences. Physical weathering is the disintegration of a rock into smaller fragments, each having the same properties as the original, and occurs mainly due to changes in temperature and pressure. Meanwhile, chemical weathering is a process by which the addition or removal of elements alters the internal structure of a mineral. Chemical weathering rates on the earth's surface are influenced by many factors, including source rock type, climatic regime, tectonic and topographic conditions, vegetation, soil development, and human activities (Meybeck, 1987; Gaillardet *et al.*, 1997), and (Oliva *et al.*, 2003).

The behavior and engineering properties of weathered rocks are influenced by the mineral composition, fabric characteristics of the rock, and the discontinuities present in the rock mass. In saprolites and residual soils, the impact of discontinuities is significantly diminished, while factors such as mineral composition, grain size, microfabric, and bonding characteristics (i.e., soil microstructure) play a more prominent role in determining the engineering properties and in-situ behavior (Irfan, 1996). The weathering process leads to alterations in the chemical composition and mineralogical structure of materials. For example, during chemical weathering, elements like calcium, sodium, and potassium can be depleted, while minerals such as feldspar are converted into clay minerals.

Indonesia's tropical climate contributes to forming soils exhibiting unique characteristics, such as swelling and contraction, associated with montmorillonite clay mineral. The soil's mineralogical composition, especially clay minerals, significantly influences geotechnical and engineering properties, impacting critical attributes like shear resistance, hydraulic conductivity, and swelling behaviour. However, studies on the weathering processes, geochemistry and mineralogy of soil formed on the tuff rock of the Semilir formation have never been carried out.

Weathering indices have facilitated geochemical studies of soils and rocks throughout geological time (Nesbitt and Young, 1982) and are commonly used to predict changes and the distribution of chemical elements (Harnois, 1988). Ruxton (1968) stated that simple indices should provide a useful guide to the physical, chemical, and engineering properties of weathered bedrock. Chemical weathering indices and direct chemical indicators such as the Weathering Index of Parker (WIP), Plagioclase Index of Alteration (PIA), Chemical Index of Weathering (CIW), Chemical Index of Alteration (CIA), and Vogt's Ratio (V) have been used as proxies in specific profiles (Shao *et al.*, 2012).

WIP was proposed by Parker (1970) for silicate rocks based on elemental mobility, which was related to the bonding strength of each element (Na, K, Mg, Ca) with oxygen. This index was most appropriate for examining the stages of soil formation in heterogeneous host rocks or homogeneous volcanic ash deposits (Price and Velbel, 2003). Since the formula of WIP only includes mobile elements, its values can differ notably from the typical values for parent rocks (Maslov and Podkovyrov, 2023). Parker's index is

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generally thought by numerous experts to be the most appropriate tool for researching the weathering processes of metasedimentary rocks (Price and Velbel, 2003). Parker's index and the degree of felsic tuff alterations in Hong Kong have a good relationship, according to Duzgoren-Aydin *et al.* (2002).

Vogt's Ratio (V) was proposed by Vogt (1927) to assess the maturity of residual sediments. High values of index V suggest intense weathering and vice versa (Maslov and Podkovyrov, 2023). Moreover, the CIA was suggested by Nesbitt and Young (1982) to quantitatively evaluate the weathering history recorded in sediments and sedimentary rocks. The index determines when feldspar will change into clay, such as kaolinite. Index CIA is used widely for estimating the chemical weathering of rocks in various locations (Dinis *et al.*, 2020; Chen *et al.*, 2021; Liu *et al.*, 2022; Fu, Jian and Pan, 2023; Maslov and Podkovyrov, 2023; Waluyo *et al.*, 2023) and others. However, this parameter is ineffective for estimating alterations at the late stages of weathering because the removal of silica dominates the process of lateralization, and SiO2 is absent in the CIA formula (Babechuk *et al.*, 2014).

CIW was proposed based on CIA but removed K_2O from the equation (Harnois, 1988). Similarly to index CIA, index CIW is believed to be an indicator of the process of feldspar transformation in clays (Nesbitt and Young, 1982; Fedo, Nesbitt and Young, 1995; Maynard *et al.*, 1995). According to the data presented in Irfan (1996), index CIW does not yield good results for processes of the weathering of granitoids. According to Duzgoren-Aydin *et al.*, (2002), the CIW index does not reflect the alteration degree of felsic tuffs. The PIA index was reported as an alternative index by *Fedo et al.*, (1995). Since silicate rocks contain high amounts of plagioclase, which dissolves faster than other minerals, the PIA can be used when plagioclase weathering needs to be monitored.

The suitability of weathering indices for various underlying bedrocks and pedogenesis circumstances has been a topic of argument for a long time (Haskins, 2006). Pedologic systems like soil are complex and cannot be fully represented by a single calculated number like a weathering index. Weathering indices may not generally apply to soils with varying source materials, climates, and taxonomies. Some indices are primarily utilized for intermediate weathering rocks, while a couple, including Bases/R_2O_3 and Bases/Alumina (Birkeland, 1999), are suggested for basic rocks. Others, such as the WIP (Parker, 1970), are also employed for acid, intermediate, and basic rocks. (Price and Velbel, 2003) asserted that the Weathering Index of Parker is best suited for analyzing the stage of soil development on diverse parent rocks or uniform volcanic ash deposits.

Few investigations have been performed to assess the weathering intensity, geochemistry, and mineralogy of soils developed on tuff rocks (Singer, 1968; Silber *et al.*, 1994; Paterno, 1999; De La Fuente, 2000; Topal, 2002; Yatno and Zauyah, 2003; Wedekind *et al.*, 2013; Ietto, Perri and Filomena, 2015; Winarti *et al.*, 2016; Permanadewi, 2017; Jo *et al.*, 2021; Seoung *et al.*, 2021; Siegesmund *et al.*, 2022). Their studies have concluded that trace element concentrations and mineralogy contents were related to the parent material type, whereas other soil-forming factors played minor roles. Although general studies on the geochemistry of soils developed from tuff rocks exist, the specific geochemical evolution of soils within the Semilir Formation has not been extensively studied. Identifying the mineral transformations during weathering, particularly how primary minerals like feldspar are altered to secondary clay minerals, could provide new insights into soil formation in this volcanic region. In particular, the objectives of this studies are : (1) to compare different weathering indices in determining the extent of tuff weathering to soil, (2) to find out the appropriate indices to assess the weathering status of soils developed on tuff rocks, and (3) to study the effect of the rate of tuff weathering on mineralogy contents.

2. MATERIALS AND METHOD

2.1 Study Area and Soil Samples

The study was conducted in the Semilir Formation, which extends from Central to East Java, Indonesia. The Semilir Formation is located in the Southern Mountains and was formed during a period of volcanism lasting from the Late Eocene to Early Miocene (Bemmelen, 1970). The volcanic rocks form the Baturagung and Gajah Mungkur Mountains, which are 45 km long, 10 km wide, and 650 m thick. The Semilir Formation in the Baturagung Mountains lies above the Kebo Butak Formation, but in some places shows misalignment (Surono *et al*., 1992). Furthermore, it overlaps with the Mandalika Formation, which is the same age as Kebo Butak in the Pacitan and Ponorogo areas (Bemmelen, 1970; Sampurno and Samodra, 1997). The formation is interbedded with Panggang, Dayakan, and Watupatok (Sampurno and Samodra, 1997). Alternative perspectives exist even though the upper Semilir Formation in the Baturagung Mountains area is locally and intermittently superimposed by the Nglanggran Formation (Surono *et al.*, 1992; Samodra and Samodra, 1997). According to Bothe and Kolhorster (1929); Bemmelen (1970); Ismoyowati (1975); Surono *et al.*, (1992), the Semilir Formation completely overlaps the Nglanggran Formation (Figure 1) and is overlain unconformably by the Oyo and Wonosari Formation. The lithology consists of tuff, lapily tuff, lapily pumice, pumice breccia, and shale (Figure 2).

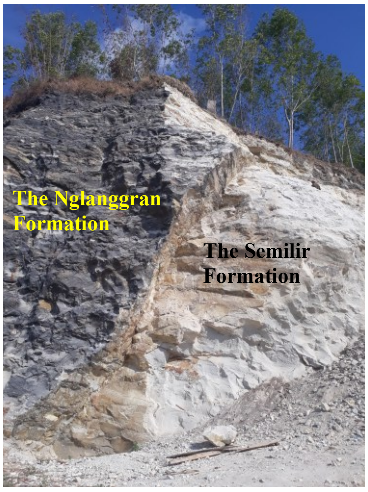

Figure 1 The Semilir Formation overlaps the Nglanggran Formation

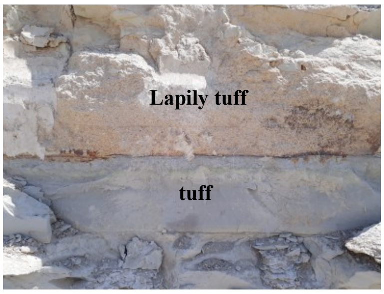

Figure 2 Lapily tuff rocks over tuff rocks

The classification of rock weathering degrees due to climatic factors, as proposed by Dearman (1976), categorizes soil into a six-fold rock weathering classification scheme, which is presented in Table 1. This scheme is also generally applicable to local igneous, volcanic, sedimentary, and metamorphic rocks in Indonesia.

A total of twelve tuff weathered soil samples were collected from the Semilir Formation to represent different weathering degree (Figure 3). The selection of sampling locations was based on the presence of tuff rock outcrops, ensuring that the collected soil samples originated from the weathering of tuff rock as the parent material. The samples were collected from research locations with varying physical conditions, aligned with the physical characteristics of rock weathering described in Table 1. Soils with weathering degree II (NLb, NLa, WP1, and WP2) exhibit physical characteristics such as a color change in the rock from off-white to light brown, with most of the material still in the form of relatively hard rock fragments that cannot be crushed by hand. Soils with weathering degree III (P1 and P2) are characterized by smaller rock fragments, a darker brown color, and can be crushed by hand. Meanwhile, soils with weathering degrees IV (S1, CS1, and CS2) and V (GM1, GM2, and S2) share similar physical characteristics, where the rock can be easily crushed by hand and the material is predominantly composed of smaller grains. The physical appearance of some of the tuff weathered soil from the Semilir Formation is shown in Figure 4.

The soils were collected at a depth of 50 cm to 100 cm after removed the visible plants and roots. Each samples were labeled and transported to the laboratory in sealed polythened bags to prevent contaminaton. All soil samples were easily get but far away from human aktivities and collected at relatively low elevations where the soils mainly originate from in situ weathering.

Table 1 A six-fold rock weathering classification scheme (Dearman, 1976)

Grade	Description	Typical characteristics
I	Fresh	Unchanged from the original state
II	Slightly weathered	Slight discoloration and weathering
III	Moderately weathered	Considerably weakened, penetrative discoloration Large pieces cannot be broken by hand
IV	Highly weathered	Large pieces can be broken by hand Does not readily disaggregate (slake) when dry sample immersed in water
V	Completely weathered	Considerably weakened Slake in water Original texture apparent
VI	Residual soil	Soil derived by in situ weathering but having lost original texture and fabric

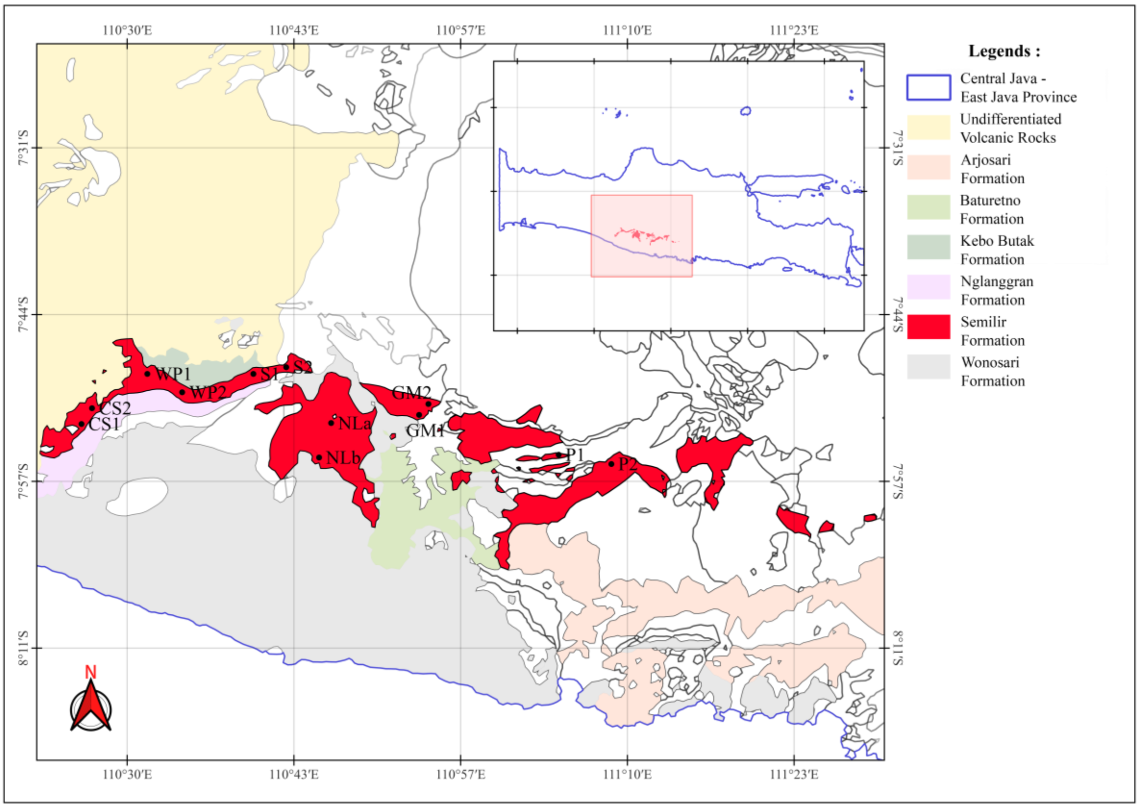

Figure 4 Location map of the study area, Candisari 1 (CS1), Candisari 2 (CS2), Watu Payung 1 (WP1), Watu Payung 2 (WP2), Semilir 1 (S1), Semilir 2 (S2), Nlipar Lapis atas (NLa) and Nlipar Lapis bawah (NLb), Gajah Mungkur 1 (GM1), Gajah Mungkur 2 (GM2), Ponorogo 1 (P1) and Ponorogo 2 (P2) (edited from Surono *et al.* (1992); Rahardjo *et al.* (1995); Sampurno and Samodra (1997).

(a) **(b)** **(c)**

Figure 3 The physical appearance of weathered tuff at different weathering degrees is as follows: (a) dominance of rock fragments in Watu Payung I soil, (b) smaller rock fragments still present in Ponorogo I soil, and (c) Semilir I soil, where small rocks can be easily crushed by hand

2.2 Chemical and Mineralogical Analysis

All soil samples were dried in an oven at 40°C for 48 hours to preserve the structure of mineral constituents. Visible stones and plant residues were picked out before grinding samples using an agate mortar. X-ray fluorescence was used to determine the soils' major oxide and geochemistry elemental abundances. The XRF detector measures the energy and intensity of the emitted X-rays. This data is used to identify the elements present and quantify their concentrations in the sample. Approximately 5 gram of soil material was ground to <60 µm and analyzed as a loose powder in a sample cup using an energy-dispersive X-ray fluorescence spectrometer. The powdered samples were analyzed using the GL-MU-2.2 Method. The X-ray powder diffraction (XRD) method was used to identify the clay minerals present in the soil samples. The X-ray patterns were obtained by placing 1 gram of soil (<2 µm) in the sample holder of an X-ray diffractometer. The Xpert Highscore software identified the mineralogical phases by comparing the peaks of pure minerals with an automatic or manual search match.

2.3 Determination of Chemical Weathering Indices

Most chemical weathering indices are based on observations of weathering of felsic and intermediate rocks under moist and well-drained environments (Ruxton, 1968; Harnois, 1988; Irfan, 1996; Duzgoren-Aydin *et al.*, 2002; Price and Velbel, 2003; Nordt and Driese, 2010; Udagedara *et al.*, 2017). This chemical weathering index uses major and trace elements with various assumptions, such as the evolution of the weathering profile and parent material composition, to show changes in intensity. (Duzgoren-Aydin *et al.*, 2002) conducted a thorough review of the index to measure the condition of weathered granite. This study also compares the weathering of Tuff weathered soils using the chemical weathering indices shown in Table 2. A positive value in the ideal tendency with the degree of weathering indicates that the chemical weathering index increases as the degree of weathering intensifies, whereas, a negative value means that the index decreases as the degree of weathering increases.

Table 2 Chemical Weathering Indices and Computational Formulas

Chemical Weathering Indices	Equation	Ideal Tendency with Degree of Weathering
Weathering Index of Parker (Parker, 1970)	(100)[2Na2O/0.35)+(MgO/0.9)+(2K2O/0.25)+(CaO/0.7)]	negative
Vogt Ratio (Vogt, 1927)	$(Al_2O_3+K_2O)/(MgO+CaO+Na_2O)$	positive
Chemical Index of Alteration (Nesbitt and Young, 1982)	$(100)[Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)]$	positive
Chemical Index of Weathering (Harnois, 1988)	$(100)[Al_2O_3/(Al_2O_3+CaO+Na_2O)]$	positive
Plagioclase Index of Alteration (Fedo, Nesbitt and Young, 1995)	$(100)[Al_2O_3-K_2O)/(Al_2O_3+CaO+Na_2O-K_2O)]$	positive

3. RESULTS

3.1 X-ray Fluorescence Spectrometry (XRF)

The samples underwent X-ray fluorescence spectrometry (XRF) analysis in this study to determine the major oxides and trace elements, a reliable indicator of tectonic setting and provenance (Gazi *et al.*, 2021). The percentages of S, Al, Fe, Ca, Mg, K, Na and Ti oxides in bulk soils are presented in Table 3. The predominant major oxide was SiO_2 (18.14% - 60.1%), followed by Al_2O_3 and Fe_2O_3, ranging from 5.39% to 20.57% and 4.82% to 14.87%, respectively, except for the NLa, NLb, and WP 1 soils with high CaO content (17.07% - 38.04%). These oxides are commonly found in the tropical climate regions. The detection of these oxides (SiO_2, Al_2O_3, and Fe_2O_3) in XRF analysis infers the abundance of kaolinite (Haruna and Kasham, 2016; Du Plessis *et al.*, 2017; Yahaya *et al.*, 2017; Annisa *et al.*, 2018). The XRF analysis also identified Minor compounds (average concentrations <1 wt%), such as MnO, MgO, K_2O, and TiO_2. Together, they constitute a little more than 2% of the total constituents of the clays, indicating a high degree of weathering.

3.2 X-ray Diffraction (XRD)

The weathering degree II samples (NLb and NLa) are predominantly composed of calcite, albite, and a minor amount of quartz (Figures 5a and 5b). The presence of calcite corresponds with the XRF results, which indicate a relatively high CaO content in these samples. In contrast, the other weathering degree II samples (WP1 and WP2) exhibit a different mineral composition, dominated by saponite (member of smectite group), calcite, mica, and a small amount of quartz (Figures 5c and 5d). The occurrence of clay minerals (saponite) in these degree II samples is likely due to their location in poorly drained areas lacking vegetation cover, leading to more intense chemical weathering processes. For the weathering degree III samples (P1 and P2), XRD analysis reveals the presence of anorthite, leakeite, and diopside (Figures 6a and 6b). According to Bowen's reaction series, anorthite is one of the first minerals to crystallize at high temperatures in igneous rocks. The absence of clay minerals in these samples may be attributed to their location in well-drained areas with vegetation cover. Meanwhile, the weathering degree IV samples contain anorthite, mica, and metahalloysite (Figures 6c and 6d). Metahalloysite is a type of clay mineral from the kaolin group or is a part of the hydrothermal alteration mineral group in geothermal fields, classified under aluminium silicate. This mineral can form at temperatures <100°C and under acidic pH conditions.

Table 3 Major Elements Composition (w/wt%)

Sample	Weathering Degree	Major Elements (%)									
		SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI
NLb	II	18.14	5.39	3.59	1.40	38.04	0.19	0.17	0.35	0.07	32.18
NLa	II	24.32	8.23	4.82	1.46	30.25	0.09	0.13	0.52	0.07	29.65
WP 1	II	22.96	10.08	6.53	1.14	29.59	0.08	0.06	0.65	0.03	28.56
WP 2	II	35.48	12.70	9.02	2.07	17.07	0.10	0.11	0.76	0.06	22.13
P 1	III	60.10	18.66	6.96	0.99	5.30	2.63	0.77	0.50	0.16	3.38
P 2	III	51.92	20.22	10.30	2.12	6.79	1.89	0.59	0.89	0.12	4.57
S 1	IV	50.69	15.35	12.84	2.68	2.59	0.43	0.30	1.22	0.04	13.25
CS 2	IV	49.80	17.86	12.80	2.25	2.01	0.32	0.42	1.22	0.05	12.74
CS 1	IV	47.76	18.75	13.86	1.86	1.87	0.27	0.40	1.14	-	13.48
GM 2	V	55.93	20.57	7.96	0.98	1.49	0.37	0.28	0.80	0.03	11.30
GM 1	V	54.97	19.22	10.13	0.96	1.35	0.35	0.33	0.76	0.03	11.48
S 2	V	44.33	19.98	14.87	1.86	1.02	0.08	0.16	1.14	0.03	15.71

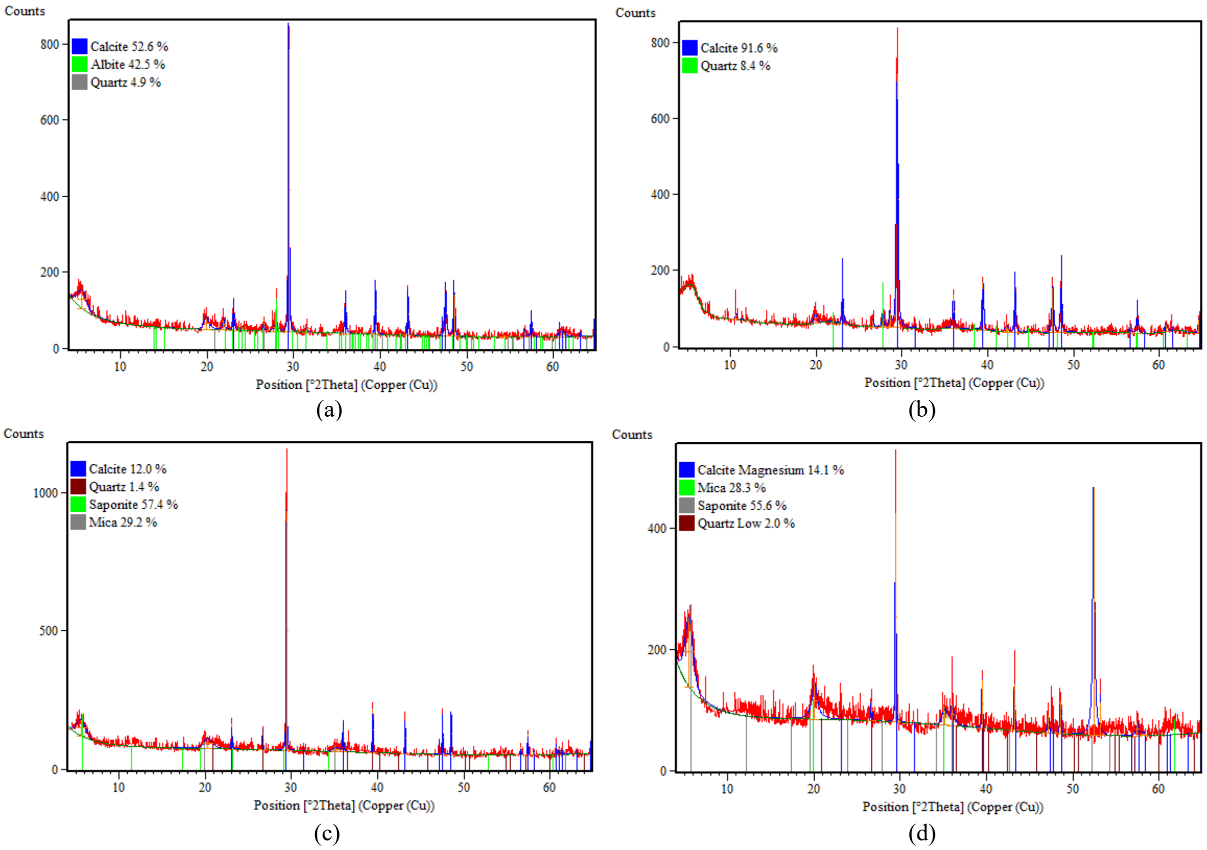

Figure 5 XRD Results for weathering degree II (a) NLb (b) NLa (c) WP1 (d) WP2

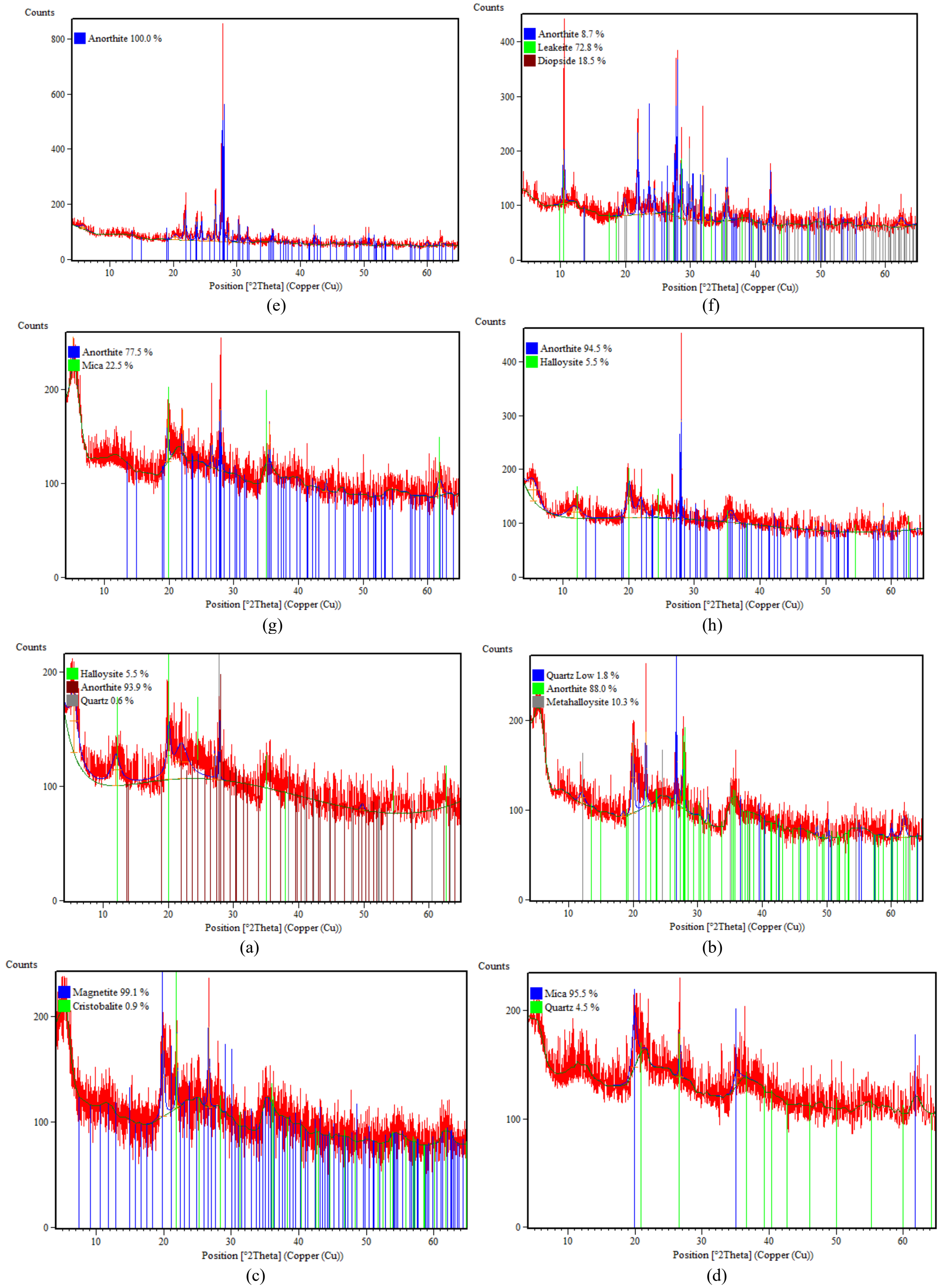

Figure 6 XRD Results for weathering degree III (a) P1 (b) P2; weathering degree IV (c) S1 (d) CS2 (e) CS1; and weathering degree V (f) GM2 (g) GM1 (h) S2

3.3 Chemical Weathering Indices

In the studied soils, the CIA rate varied from 12.31 to 88.07. The CIA values increased with weathering (Figure 7). Upon evaluation per the CIA, four samples had a CIA value of less than 50, lower than the weathering index for a fresh rocks. Depending on the CaO content ratio, rocks with high CaO volume may exhibit weathering indices that show results in the irrelevant range. Harnois (1988) stated that the value of CIW increased with weathering. Table 4 and Figure 7 show that the CIW values range between 12.31 and 94.08 and tend to increase with the weathering degree. The WIP was the most appropriate for applications to weathering profiles on heterogeneous (and homogeneous) parent rock (Price and Velbel, 2003). The WIP values in these studied soils were distributed between 5.28 and 58.32. The values of WIP decreased with weathering (Figure 7).

Since plagioclase is abundant in silicate rocks and dissolves relatively quickly, the PIA can be used when the weathering needs to be monitored. The PIA values show similar sample variations and range from 12.01 to 94.78. The PIA values show similar sample variations and range from 12.01 to 94.78. The values show an increasing trend with the degree of weathering, similar to CIW and CIA (Figure 7). Increasing V values indicate an increasing intensity of weathering. The V values in this study varied from 0.14 to 7.35, and Figure 7 showed that the V values tend to increase with weathering degree.

Table 4 Chemical Weathering Indices

Sample	WIP	V	CIA	CIW	PIA
NLb	58.32	0.14	12.31	12.36	12.01
NLa	46.40	0.26	21.27	21.34	21.07
WP 1	44.47	0.33	25.32	25.36	25.25
WP 2	28.13	0.67	42.36	42.51	42.31
P 1	29.85	2.18	68.21	70.18	69.29
P 2	27.58	1.93	68.57	69.97	69.34
S 1	11.55	2.75	82.21	83.57	83.29
CS 2	10.50	3.99	86.69	88.48	88.24
CS 1	9.48	4.79	88.07	89.75	89.55
GM 2	7.59	7.35	90.57	91.72	91.61
GM 1	7.63	7.34	90.44	91.86	91.73
S 2	5.28	6.82	94.08	94.82	94.78

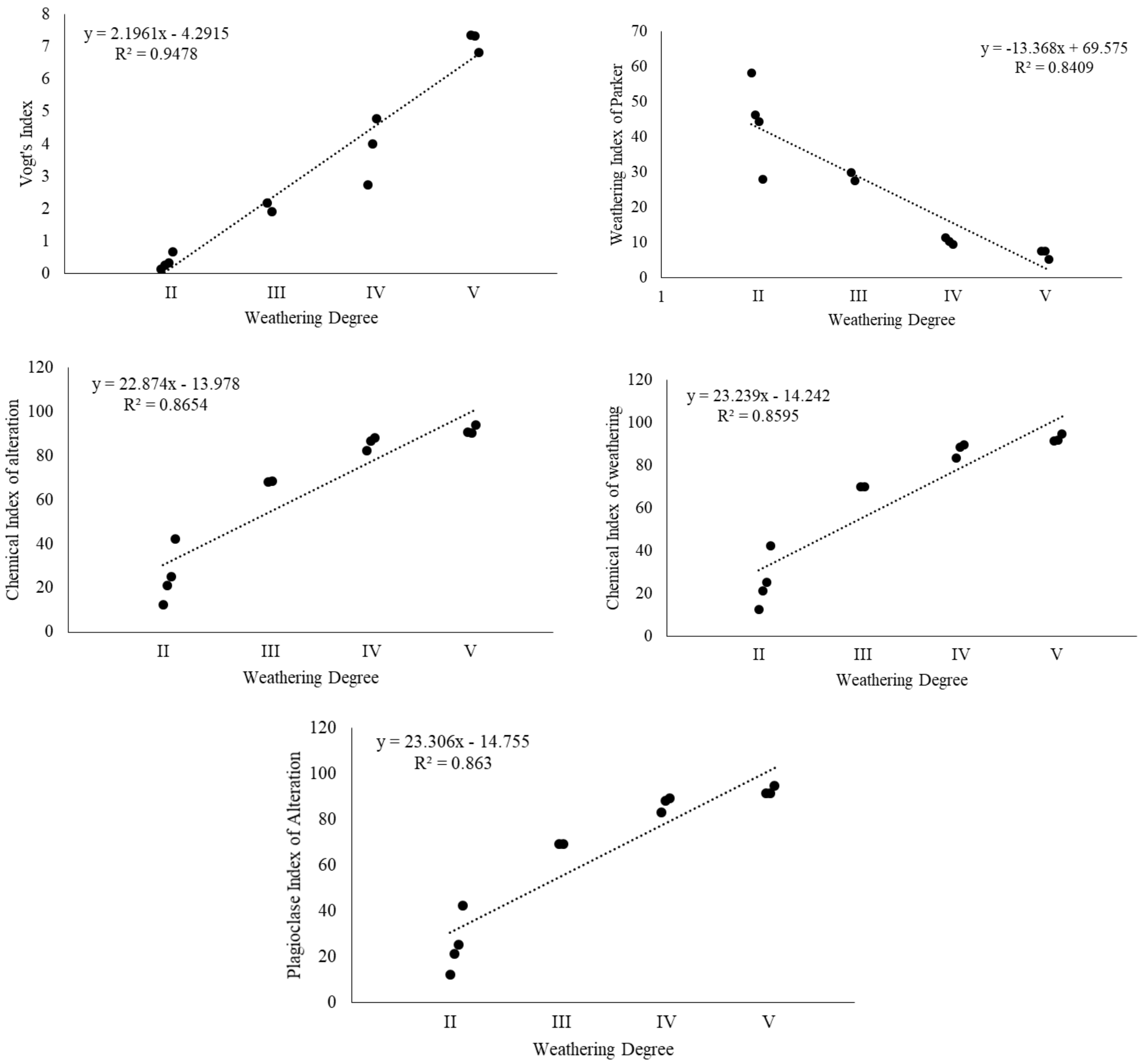

Figure 7 The relationship between chemical indices and soil weathering degree

4. DISCUSSIONS

4.1. Geochemistry and Mineralogy

The chemical composition of the soil estimated by XRF testing shows that the content of SiO_2, Al_2O_3, Fe_2O_3, and TiO_2 in the weathered tuff soil of the Semilir Formation increases with the degree of weathering (Figure 8), while MgO, Na_2O, and K_2O did not show a consistent decreasing tendency with weathering (Figure 9). SiO_2 is highly resistant to weathering due to its quartz mineral content. In contrast, Al_2O_3 is less resistant because of the clay minerals (Shan *et al.*, 2010; Husain, 2015), and the highest amount of Fe_2O_3 (14.87%) is found in S2. Samples with weathering degree II have high CaO content and low SiO_2 compared to others (range 17.07% to 38.04%). These four weathered soils most likely come from carbonate parent rocks with less than 40% SiO_2 and CaO. Figure 9 represents the negative correlation between CaO % and the degree of weathering. Considering Figure 8, it can be concluded that enhanced silicate weathering is commonly associated with carbonate leaching. Therefore, since more developed soils were located on carbonatic parent materials, this kind of correlation could be reasonable. This study demonstrates the relationship between the weathering degree based on a six-fold rock weathering classification scheme with chemical weathering indices and its mineralogical content.

The CIA values are classified into slightly weathered (50-60), weathered (60-70), moderately weathered (70-80), very weathered (80-90), and highly weathered (90-100) (Nesbitt and Young, 1982). Upon evaluation per the CIA classification, four samples have a CIA value of less than 50, lower than the weathering index for a fresh state; two samples are moderately weathered, three are highly weathered, and three are extremely weathered. If the classification for CIA is performed for CIW, it is evident that all the soils have different parent materials and are located in different topographic positions. The soils studied have some morphological differentiation and are affected by different weathering conditions. Regarding WIP, the values between 80 and 100 are for fresh rock and values between 0 and 70 generally show high weathering degree. The data demonstrate that the studied soil has WIP values <70, which indicates the soils have been weathered from fresh rock to weathered soil.

XRD test results indicate that some samples contain clay minerals, namely Metahalloysite and saponit. Metahalloysite and saponit can still transform into other clay minerals as weathering continues, eventually reaching the final stage of weathering known as residual soil. This proves that the soil samples in this study are in weathering stages II to V.

A similar study was conducted on soils derived from pyroclastic materials Chichester *et al.* (1969). They documented the presence of smectite and linked changes in the soil to rainfall and temperature. According to Duzgoren-Aydin *et al.* (2002), weathered pyroclastic soil samples in Hong Kong contain vermiculite and smectite clay minerals, but only in small quantities. Due to minimal drainage conditions and soil lacking chemical and physical characteristics such as low electrical conductivity, low pH, soluble anions, and low cations, these minerals were notably low. The amount of smectite decreased with elevation, influenced directly by temperature, leaching, and dilution of soil extracts due to rainfall and an increase in slope steepness. The mineralogical composition of the studied samples also includes metahalloysite, a type of kaolinite; considering regional conditions, its presence should be considered geogenic. According to Raheb and Heidari (2012), the soil formation process in the arid zones of Iran is unlikely to lead to the formation of kaolinite. Irfan (1996) suggests that some occurrences of kaolin are associated with hydrothermal activity, but Parry *et al.* (2002) states that most kaolin distribution and presence are linked to weathering processes and hydrothermal alterations that occur only locally. Halloysite minerals indicate that the geotechnical properties are still changing or that these clay minerals are still young (Dixon, 2018).

Research on weathered tuff soils from the Semilir Formation has yielded varied results. Soil samples containing saponite and metahalloysite were collected from higher elevations than soil samples that did not contain these clay minerals or other clay minerals. This difference may be attributed to lower temperatures at higher elevations. During the rainy season, areas at higher elevations receive more rainfall compared to areas at lower elevations.

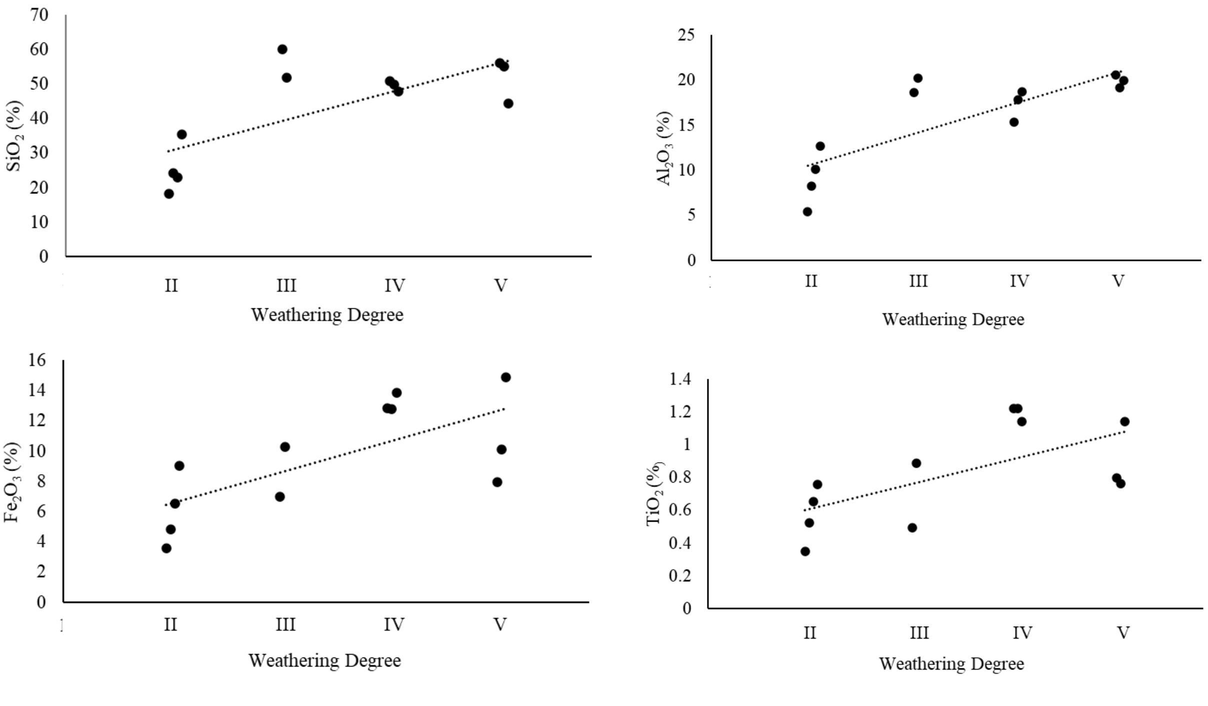

Figure 8 The relationship between SiO_2, Al_2O_3, Fe_2O_3, TiO_2 and soil weathering degree

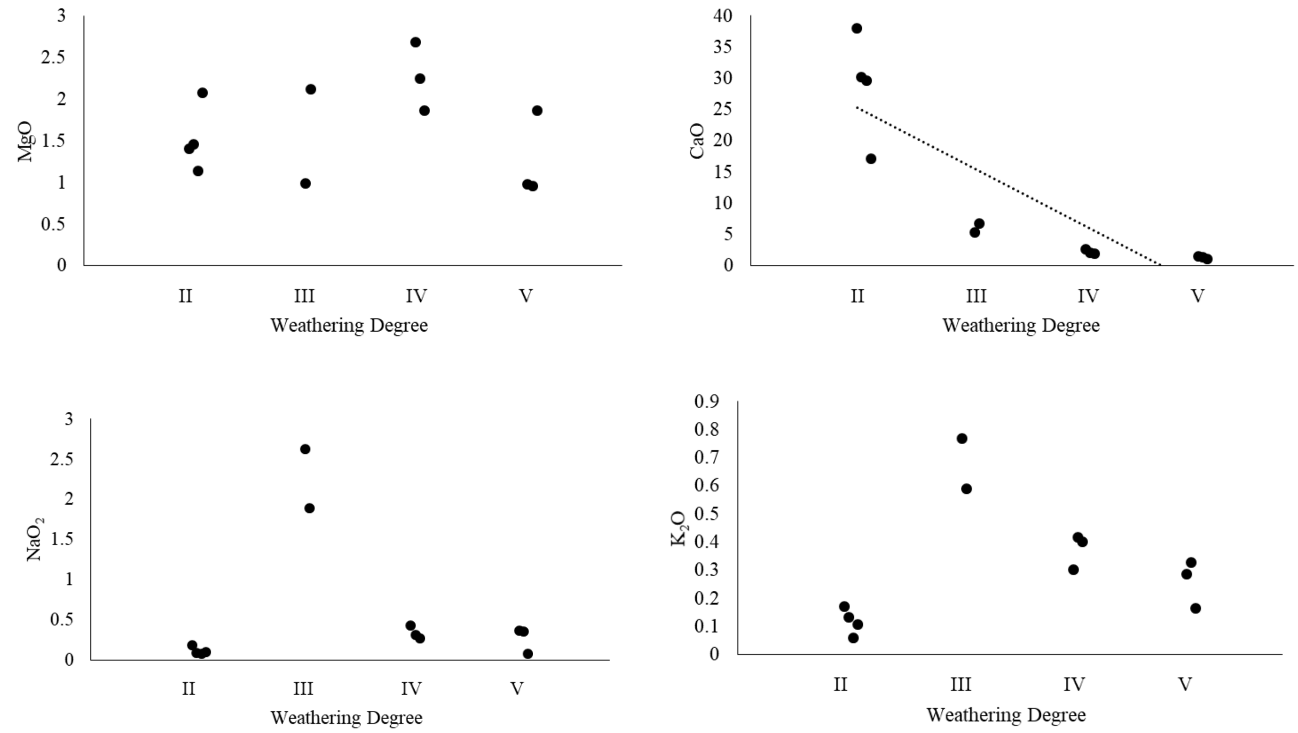

Figure 9 The relationship between MgO, CaO, NaO_2, K_2O and soil weathering degree

4.2. Chemical Weathering Indices

In order to determine the relationship between the chemical indices, simple regression analyses were undertaken. The results with the highest coefficients are shown in Figure 10 and Figure 11. All the indices showed a reasonably good relationship with other indices. CIW and CIA show a very good correlation (≈ 100%) because CIW is a modified chemical weathering index from the CIA. WIP and CIA, WIP and CIW, and WIP with PIA also show good relationships (>90%). These well-correlated weathering indices consistently reflect significant source chemical weathering degree. Among the correlations between chemical weathering indices, only Vogt's Ratio shows a 73% correlation with the PIA (Figure 11). Its relationship with other weathering indices is not discussed in this study, and therefore, no further conclusions can be drawn.

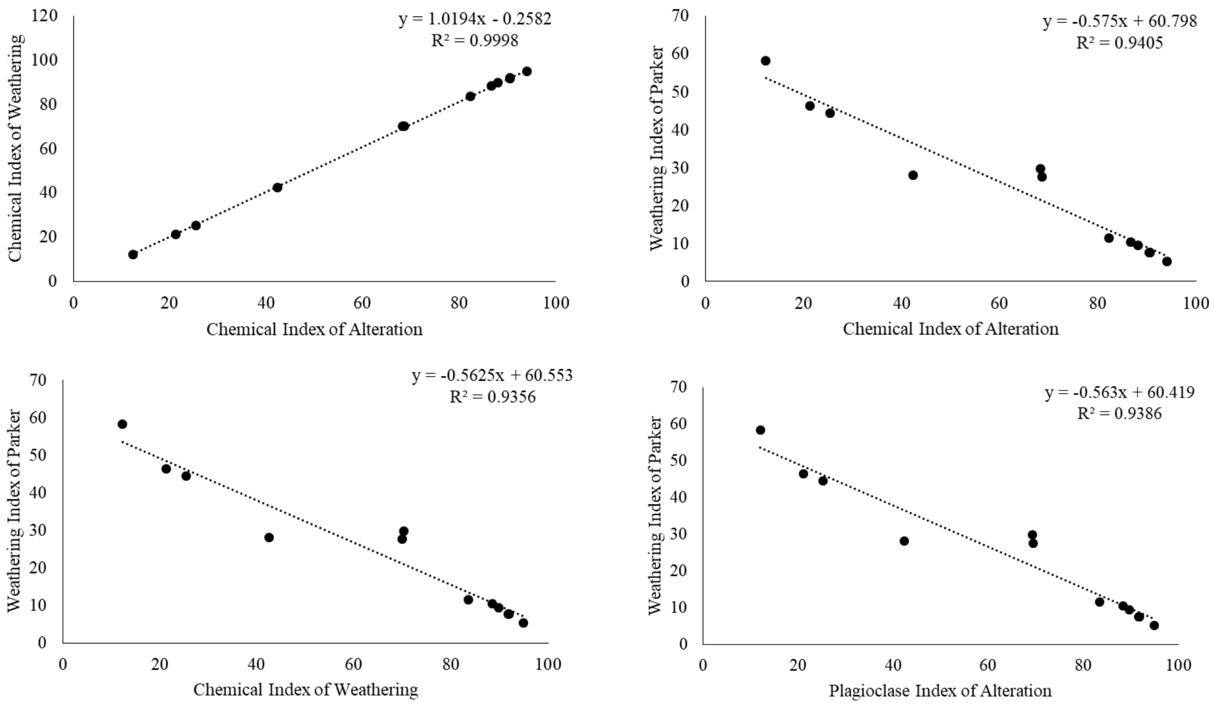

Figure 10 The relationship between chemical weathering indices

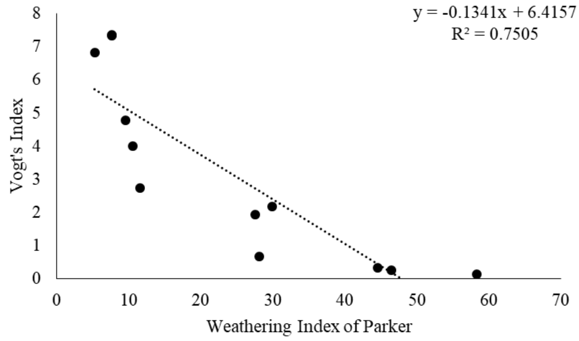

Figure 11 The relationship between chemical weathering indices

5. CONCLUSIONS

This study demonstrates the relationship between the weathering level based on a six-fold rock weathering classification scheme with chemical weathering indices and its mineralogical content. XRD test results indicate that some samples contain clay minerals, namely Metahalloysite and saponite. These clay minerals can still transform into other clay minerals as weathering continues, eventually reaching the final stage of weathering known as residual soil. This proves that the soil samples in this study are in weathering stages II to V.

The chemical composition of the soil, estimated through XRF testing, reveals that the content of SiO_2, Al_2O_3, and Fe_2O_3 in residual tuff soil increases with the degree of weathering. At the same time, CaO decreases with the degree of weathering. MgO, Na_2O, K_2O, and TiO_2 correlate poorly with the degree of weathering. The chemical weathering indices in this study indicate that have a good correlation with the degree of weathering. The Chemical weathering indices that show a good correlation with the degree of weathering include The Weathering Index of Parker (WIP), The Chemical Index of Alteration (CIA), The Chemical Weathering Index (CIW), and The Plagioclase Index of Alteration (PIA). In order to determine the relationship between the chemical indices, simple regression analyses were undertaken. All the indices showed a reasonably good relationship with other indices.

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