Minerology and chemical propertries of residual soils

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Abstract: The Khao Luang Mountain Range in the southern Thailand consists predominantly of granite and granitic gneiss, which have been weathered to varying depths. Rainfall triggered landslides and associated floods in the Khao Luang Mountain Range have caused hundreds of deaths and millions of dollars of property damage in 1958, 1964, 1975, 1981 and 1988. Field mapping indicates that most of landslides involving residual soil (weathering grades V and IV) have been transformed into debris flows and that the boundary between weathering grades IV and III generally formed the landslide slip surface. As part of research to investigate the mechanism of debris flow initiation, an extensive field and laboratory testing program was carried out to understand the behaviour of the weathered granite in the Khao Luang Mountain Range. This paper presents the results of laboratory tests carried out to determine chemical and mineralogical properties of weathered granite, in an attempt to determine appropriate mineralogical and chemical weathering indices for weathered granite in the Khao Luang Mountain Range.

Major minerals in the sand fraction include quartz (20% to 55%), biotite (5% to 65%), feldspar (10% to 25%) and hematite (2% to 30%). The quartz and hematite content increase and the biotite content decreases with degree of weathering. Feldspar content increases with degree of weathering. The sand fractions also contain minor proportions (less than 5%) of tourmaline, magnetite, hornblende, illite, zircon, rutile etc. In clay and silt fractions, kaolin shows an increasing trend and illite a decreasing trend with degree of weathering. Element analysis indicates that SiO_2 content of weathered granite increases whereas the Al_2O_3, Fe_2O_3 and MgO content decreases with the degree of weathering. The K_2O and CaO do not show a distinct correlation with the degree of weathering.

This paper also discusses appropriate mineralogical and chemical weathering indices for the weathered granite in the Khao Luang Mountain Range.

Résumé: Le Khao Luang reageé de montagne du sud Thailand consister prédomine de granite et granite genése. Quets temps ont varie et profound. La pluie détente de éboulement de terrain et a associé inundation dans la rangeé de montagne de dans Le Khao Luanga cause de mort de cents de gens et propriéte dommages que a perdu millions d`argent en 1958, 1964, 1975, 1981 et 1988. Le plus éboulement sol (enclimant grade v et iv) a mobisisé à courant glissade surface. Prendre part faire une enquête sur la mé canisme de debris du courant commencer, une extensive le champ et laboratoire en examinant programme à été mettre en pratique, pour compendre la comporte de temps grainite dans la KhaoLuang montagne Rangeé. Ce papier present le résultat de laboratoire examen en pratique à fixer chimique et mimerologique proprié té de temp granite, essayer à fixer appropriate minorologi que et chemique en climent index pour en temps granite dans le Khao Luang montagne Rangeé.

Majeur minerals dans la sable embrasser sont quartz (20% à 55%) bilotite (5% à 65%) feldspar (10% à 25%) et hematite (2% à 30%) le quartz et hematite contenter augmentant, biotite décroissance avec degré de temps. Feldspar contenter indicater en augmentant direction avec degree de temps. La sable fractions aussi container petit proportion (Moins que 5%) de tourmaline, magnetite, hornblende, illite, zircon, rutile etc. La argile et vase fractions, kaolin montre à en dé croissant direction avec degree de temps. element analyse indicater cela SiO2 contenter de temps granite augamentation comme Al2O3, Fe2O3 et MgO décroissance avec la degree de temps. Le K2O et Ca One fait pas montre un distinct correlation avec la degree de temps.

Ce Papier aussi discuter appropriate minerologique chemique temps index pour le temps granite dans le Khao Luang Montagne Rangeé.

Keywords: clay minerals, igneous rocks, index tests, mapping, triaxial tests, weathering

INTRODUCTION

The Khao Luang Mountain Range in the southern Thailand consists predominantly of granite and granitic gneiss. The bedrock has been weathered to varying depths and residual soil is the most widespread surface deposit. The mountain range has recorded history of landslides. Rainfall triggered landslides and associated flooding have caused hundreds of deaths and property damage worth millions of dollars in 1958, 1964, 1975, 1981 and 1988 (Jworchan & Nutalaya, 1994). Many landslides were transformed into debris flows, which were the most important cause of the death and property damage (Jworchan, 1995).

Field mapping after the landslide disasters in 1988 indicated that most of those that were transformed into debris flows involved granite of weathering grade V and IV (residual soil) and that the boundary between weathering grade IV and III generally formed the landslide slip surface. The weathering grade classification is based on Dearman et al (1978). Topography, groundwater conditions and the engineering properties of materials determine whether a landslide is transformed into a debris flow.

As part of a research to investigate the mechanism of debris flows initiation in the Khao Luang Mountain Range, an extensive field and laboratory testing program was carried out, to understand the behaviour of the weathered granite.

This paper presents the results of laboratory tests carried out to determine chemical and mineralogical properties of the weathered granite, in an attempt to determine appropriate mineralogical and chemical weathering indices.

Samples of weathered granite for the study were collected from four different weathering profiles in the Lham Nah Creek Basin (study area) in the Khao Luang Mountain Range (Figure 1).

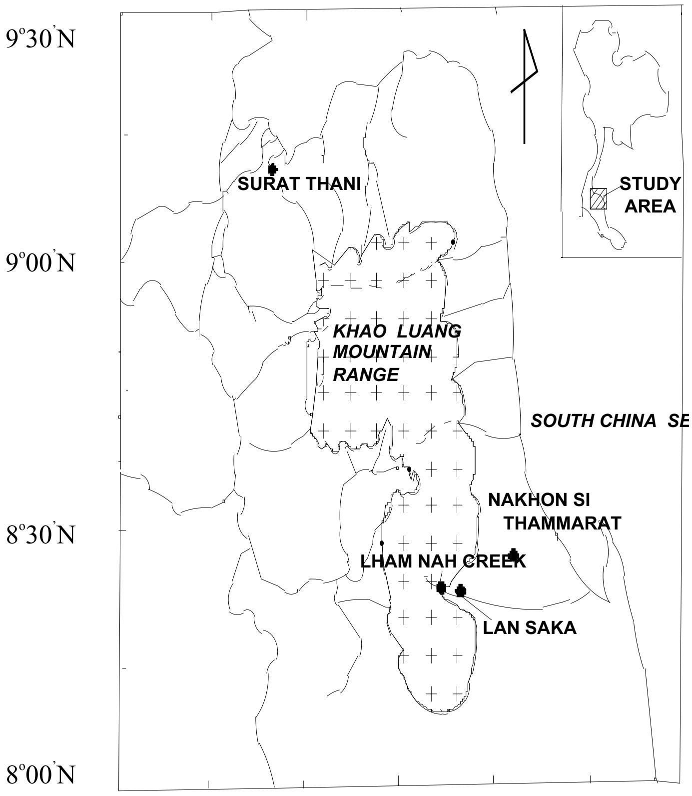

Figure 1 Lham Nah Creek in the Khao Luang Mountain Range

BEDROCK

The Khao Luang Mountain Range consists of a core of metamorphosed igneous rocks, flanked by sedimentary rocks, which are overlain by thick deposits of Quaternary deposits. Within the Lham Nah Creek Basin (study area), granite is the only bedrock. The granite is coarse grained, slightly metamorphosed, foliated (Nakapadungrat, et al., 1987) and free of major discontinuities. Intrusions of quartz veins and aplite dikes were observed at many places. Results of modal analysis of a typical granite sample from the Lham Nah Creek Basin is given in Table 1.

Residual soil (68.5%) is predominant surface deposit within study area, with some colluvium (15.5%), debris flow deposits (2.0%), laterite (0.5%) and bedrock outcrops (13.5%).

Table 1. Mineral composition of granite from the study area

Mineral Name	Composition* (%)
Plagioclase	30
Biotite	20
Quartz	20
Potassium Feldspar	10
Muscovite	10
Zircon	Trace

* Approximate only

WEATHERING PROFILE AND RESIDUAL SOILS

Weathering profiles at four locations within the Lham Nah Creek basin (designated as site-K, site-T, site-TW and site-W) were investigated in detail using the weathering classification system of Dearman et al (1978). According to this system, the weathering profile is divided into six grades, I to VI. Above the fresh bedrock (grade I), the slightly weathered and moderately weathered zones (grades II and III) tend to behave in engineering terms as rock. Weathered granite of grade V to grade VI tends to behave in engineering terms as soils and are termed residual soil (Geological Society Engineering Group, 1990). The boundary between grade III and grade IV represents an important transition in engineering behaviour from rock in which behaviours may be controlled by movements along discontinuities, to a soil where behaviour is controlled by mass deformation.

A complete weathering profile, comprising materials of weathering grades I to VI was not observed at any single location within the study area but materials of all weathering grades were exposed at different locations. As an example, description of weathering profile at site-T is presented in Table 2 below:

Table 2. Description of weathering profile at site-T in the Lham Nah Creek Basin

Depth (m)	Weathering Grade	Soil Description
0.00-0.15	Topsoil	Clayey Sand, coarse grained, loose, dark yellowish brown, abundant roots.
0.15-0.60	VI	Clayey Sand, medium to coarse grained, yellowish brown to olive brown, loose, abundant roots, no rock texture
0.60-1.10	VI/V	Clayey Sand, medium to coarse grained, light olive brown, loose to medium dense, weathered feldspar evident, rock texture discernable.
1.10-1.80	V	Clayey Sand, medium grained, light olive brown, medium dense, rock texture distinct.
1.80-2.00	IV	Clayey Sand, medium grained, medium dense, yellowish brown.
2.50	Grade III rock surface along which landsliding has taken place	

The weathering profiles in the study area have the following general characteristics:

- They are relatively thin and incomplete, because the slopes in the area are typically steep, and erosion during rainy seasons has truncated profiles and prevented thick accumulation of residual soils.
- Grade VI material is generally 0.5m to 2.0m thick and is overlain by 0.3m to 0.5m thick topsoil. At some locations, the grade VI material has been desiccated and hardened (laterized).
- Grade V and IV material is generally less then 2.0m.
- The boundary between grade VI and V is distinct, whereas the boundary between grade V and IV is gradational.
- Grade IV material is underlain by materials of variable weathering grades, grades III to fresh bedrock.
- The weathering profiles rarely show presence of corestones.

PHYSICAL PROPERTIES

As samples were collected at the end of a rainy season, the natural moisture content of the soil lies within a narrow range of 15-17 %, irrespective of the degree of weathering or the depth. Specific gravity does not vary much within grade VI to grade IV materials and is in the range of 2.65-2.66. For materials of weathering grade III-II, the specific gravity is about 2.75.

The clay content increases with the degree of weathering. For grade VI and V materials the clay content varies from 10% to 50%, and the average value is about 27%. Average clay content for grade IV-III materials is about 18%. The silt content shows no significant variation with the degree of weathering, but sand content decreases with increasing degree of weathering.

Atterberg limits tests show that the grade VI and V materials have liquid limit, plastic limit and plasticity index in the range of 30-87%, 18-50% and 8-43%, respectively. There is a tendency for the liquid limit and plastic limit to increase with degree of weathering, while the opposite is true for plasticity index. Most materials of grade III to grade II are non-plastic. All weathered granites cluster around the A-line. Grade VI materials plot both above and below the A-line but grade V-IV materials usually lie below the A-line.

Grade VI-IV materials have a similar total unit weight of about 16 kN/m^3 and a void ratio of about 0.9 but these values are 18 kN/m^3 and 0.7 for grade III-II materials. The degree of saturation decreases from 65% for grade III-II materials to about 44% for grade VI-V materials. The unit weight generally increases with depth while porosity decreases with the depth.

STRENGTH PROPERTIES

The internal friction angle of residual soils (grade VI to V) as determined by the direct shear test is in the range of 35 to 45^o. These values do not change with the degree of saturation. Most samples show a value closer to the lower value. The cohesion depends on the degree of saturation. At natural moisture content (15 to 20%), the cohesion value is in the range of 15 to 50 kPa. Cohesion is generally less that 15 kPa under submerged condition (Jworchan 2000).

In triaxial tests, weathered granite of grade VI to V shows a peak in strain-stress curves and an increase in pore pressure during shearing, indicating a relatively loose, compressible soil type. Grade IV to III granite show strain-hardening behavior, whereby pore pressures initially rise and then decrease with shear. This indicates that grade IV to III granites are compressible in natural conditions but once failure is initiated the shearing continues as in a dilative material. The grade IV to III granites usually show a planar shear surface indicating a strong influence of discontinuities, inherited from the parent rock. Samples tested during a stress path triaxial condition have smaller cohesion (about 2.5 kPa) and higher values of internal friction angle (about 45^o). In the undrained triaxial condition, many samples showed no cohesion, though some samples did show a higher cohesion, and friction angles in the range of 30-45° (Jworchan 2002).

MINERALOGY

In the study of tropical residual soil the influence of mineralogy and soil microstructure are very important, especially if the soil contains minerals prone to swelling. Typically, soils containing less the 15% clay minerals behave much as a granular materials. Cohesive behaviour dominates if soils contain more then 40% clay minerals (Geological Society Engineering Group, 1990). The coarser fraction is generally derived directly from the parent rock whereas the finer fraction is a secondary product of weathering. To study mineral constituents of weathered granite, the samples were separated into sand, silt and clay fractions.

The minerals in fine sand were identified using petrographic microscope and X-ray diffraction was used to identify minerals present in silt and clay fractions. Both petrographic analysis and X-ray diffraction analysis give approximate composition of different minerals. X-ray diffraction analysis requires pre-treatment of clay samples. In general, pre-treatment involves separation of silt and clay fraction, removal of iron and preparation of magnesium and potassium saturated clay samples. To identify types of clay minerals, five x-ray diffraction tests were run for each clay specimen. For each test the specimen was prepared differently. They were (1) iron removed and magnesium saturated (2) iron removed, magnesium saturated and glycolated (3) iron not removed and magnesium saturated (4) potassium saturated and (5) potassium saturated and heated to 550°C. The proportion of sand, silt and clay in weathered granite samples and mineral composition of fine sand, silt and clay fractions in the samples are presented in Table 3 to Table 5.

Table 3. Textural composition and weathering grade

Textural Composition	Weathering Grade III		Weathering Grade IV		Weathering Grade V		Weathering Grade VI	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Coarse Sand (%)	17.8-29.1	23.5	15.7-33.3	24.0	14.4-32.7	24.1	24.5-36.2	29.7
Medium Sand (%)	24.8-29.9	28.1	19.6-29.7	24.3	17.4-26.0	21.3	17.5-28.2	21.8
Fine Sand (%)	18.1-27.8	22.4	11.3-21.5	15.9	7.7-20.5	13.6	3.3-15.7	10.4
Total Sand (%)	69.5-81.8	73.9	52.6-78.4	64.2	44.3-67.8	59.0	49.5-67.9	61.9
Silt (%)	9.9-17.1	11.7	10.9-21.2	15.0	9.0-17.6	12.9	8.3-16.3	11.2
Clay (%)	7.9-20.6	14.3	10.3-32.2	20.8	16.9-39.1	28.1	17.8-40.6	26.9

Table 4. Mineral composition of silt and clay fractions

Textural Composition	Weathering Grade III		Weathering Grade IV		Weathering Grade V		Weathering Grade VI	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Vermiculite (%)	0.0-25.7	25.8	0.0-14.8	4.1	0.0-3.5	0.5	0.0-1.8	0.4
Illite (%)	18.8.3-34.3	34.3	19.0-35.6	28.2	11.5-48.2	33.7	5.8-51.4	29.3
Kaolinite (%)	46.3-93.2	93.2	50.4-73.3	64.6	51.8-88.5	63.4	48.6-94.2	70.3

Clay is one of the most important constituents of the residual soil. Clay content and clay type influence basic properties, strength properties as well as chemical properties. Liquid limit decreases with increasing vermiculite and illite but the opposite is the case for kaolinite. The cohesion increases and internal friction angle decreases with increasing clay content.

Table 5. Mineral in composition of fine sand fraction

Textural Composition	Weathering Grade III		Weathering Grade IV		Weathering Grade V		Weathering Grade VI	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Quartz (%)	21.0-48.0	34.3	20.0-38.0	30.7	18.0-52.0	30.4	28.0-56.0	39.8
Hornblende (%)	1.0-4.0	3.1	2.0-3.0	2.3	1.0-7.0	3.3	2.0-5.0	3.2
Tourmaline (%)	1.0-3.0	1.8	1.0-2.0	1.4	0.0-5.0	2.3	1.0-2.0	1.2
Biotite (%)	19.0-52.0	36.0	27.0-37.0	32.0	13.0-65.0	39.8	6.0-41.0	24.7
Feldspar (%)	10.0-24.0	16.1	10.0-22.0	14.8	7.0-18.0	13.5	11.0-27.0	17.4
Magnetite (%)	1.0-3.0	2.1	2.0-9.0	4.2	1.0-6.0	3.0	1.0-5.0	3.3
Hematite (%)	2.0-13.0	6.3	4.0-28.0	13.3	1.0-13.0	6.5	2.0-17.0	8.9
Illite (%)	0.0-2.0	1.0	1.0-2.0	1.5	1.0-3.0	1.5	1.0-20.	1.4
Zircon (%)	1.0-3.0	1.5	1.0	1.0	1.0-2.0	1.3	1.0-2.0	1.3
Rutile (%)	None	None	None	None	1.0	1.0	1.0	1.0

In general terms the major minerals in the sand fraction are quartz (20% to 55%), biotite (5% to 65%), feldspar (10% to 25%) and hematite (2% to 30%). The quartz and hematite content increase, whereas biotite decreases with degree of weathering. Feldspar content indicates an increasing trend with degree of weathering, but the correlation is not distinct. The sand fractions also contain minor proportion (less than 5%) of tourmaline, magnetite, hornblende, illite, zircon and rutile. In clay and silt fractions, kaolinite (45% to 95%) shows and increasing trend and illite (20% to 50%) shows decreasing trend, with degree of weathering. The vermiculite content is minor.

CHEMICAL PROPERTIES

As suggested by Geological Society Engineering Group (1990), chemical properties of weathered granite were assessed in terms major elements, using x-ray fluorescence spectroscopy. The elements and assessed chemical composition in weathered granite are presented in Table 6 and Table 7.

Table 6. Elemental compositions of weathered granite

Elemental Composition	Weathering Grade III		Weathering Grade IV		Weathering Grade V		Weathering Grade VI	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Si (%)	29.00-31.30	29.81	27.50-33.50	29.99	23.60-31.90	28.72	29.60-36.10	32.59
Al (%)	9.74-11.50	10.45	8.35-11.70	10.37	9.22-14.30	11.04	6.18-11.00	9.12
Fe (%)	3.77-5.45	4.79	4.05-6.38	5.05	3.81-5.59	4.75	2.10-4.68	3.50
Ti (%)	0.46-0.78	0.67	0.54-0.72	0.64	0.47-0.88	0.62	0.41-0.64	0.52
Na (%)	0.07-0.96	0.28	0.10-0.33	0.16	0.07-0.50	0.24	0.06-0.48	0.24
Mg (%)	0.17-0.93	0.62	0.43-0.84	0.60	0.21-0.89	0.62	0.15-0.61	0.36
K (%)	1.09-4.86	2.86	2.25-3.51	2.90	1.12-4.22	2.92	0.84-4.20	2.70
Ca (%)	0.02-0.77	0.15	0.07-0.28	0.12	0.01-0.46	0.14	0.01-0.16	0.06
S (ppm)	25.0-130.0	86.67	25.0-105.0	55.71	35.0-135.0	66.92	35.0-155.0	77.78
P (ppm)	320.0-545.0	414.44	310.00-885.0	523.57	350.0-720.0	453.46	310.0-465.0	385.00
Mn (ppm)	95.0-490.0	340.00	140.0-375.0	264.29	140.0-460.0	291.15	110.0-425.0	222.78
Cl (ppm)	50.00-260.00	168.33	45.00-205.00	127.14	55.0-210.0	133.08	45.0-130.0	71.67
Cu (ppm)	10.00-55.00	16.67	10.00-15.00	12.86	5.00-15.00	11.15	5.00-10.0	7.22
Zn (ppm)	45.0-100.0	73.89	70.0-85.0	74.29	50.0-80.0	74.23	30.00-75.00	50.00

Table 7. Assessed chemical composition of weathered granite

Chemical Composition	Weathering Grade III		Weathering Grade IV		Weathering Grade V		Weathering Grade VI	
SiO_2 (%)	62.04-66.97	63.77	58.83-71.67	64.15	50.49-68.24	61.43	63.32-77.23	69.72
Al_2O_3 (%)	18.4021.73	19.74	15.78-22.11	19.59	17.42-27.02	20.87	11.68-20.78	17.23
Fe_2O_3 (%)	5.58-8.06	7.09	5.99-9.44	7.47	5.64-8.27	7.03	3.11-6.92	5.18
K_2O(%)	1.31-5.85	3.44	2.71-4.23	3.50	1.35-5.08	3.52	1.01-5.06	3.25
Na_2O (%)	0.09-0.29	0.37	0.13-0.44	0.21	0.09-0.67	0.32	0.08-0.65	0.33
CaO (%)	0.03-1.08	0.20	0.10-0.39	0.17	0.01-0.64	0.20	0.01-0.22	0.09
MgO (%)	0.59-3.23	2.15	1.49-2.91	2.07	0.73-3.09	2.16	0.52-2.12	1.26

Chemical composition of weathered granite estimated from element analysis indicates that SiO_2 content of weathered granite increases with the degree of weathering whereas Al_2O_3, Fe_2O_3 and MgO decrease with the degree of weathering. The K_2O and CaO do not show a distinct correlation with the degree of weathering.

WEATHERING INDEX

Weathering affects almost all engineering properties of the rock and in most cases the effect is unfavourable, because it reduces both the strength and stability Vaughan *et al*. (1988). Weathering brings about changes in chemical and mineralogical composition of the rock (Irfan & Dearman 1978). For engineering applications it would be beneficial to obtain a correlation between engineering properties and degree of weathering. The degree of weathering is represented by some indices, be it chemical, mineralogical or physical.

Petrographical properties, which can affect engineering behaviour of rocks, are mineral composition, alteration products, grain structure, texture, types and amount of microcracks, fillings and anisotropy, if any (Ifran & Dearman 1978). One of the most widely used mineral weathering indices is ratio of quartz to feldspar, the higher the ratio the greater the amount of chemical decomposition. Olivine, amphibole and pyroxene are least stable; zircon, tourmaline are most stable. Thus ratio of zircon or tourmaline to amphiboles and pyroxenes provide an indication of the stage of chemical weathering. Some chemical indices of the degree of weathering are as follows:

Weathering potential index (WPI) (Reiche 1943)

$WPI=(K_2O+Na_2O+CaO+MgO-H_2O)*100/ (SiO_2+Al_2O_3+Fe_2O_3+FeO+TiO_2+CaO+MgO+Na_2O+K_2O)$

Product iIndex (PI) (Reiche, 1943)
$PI = SiO_2*100 / (SiO_2+Al_2O_3+Fe_2O_3+FeO+TiO_2)$

Silica-sesquioxide ratio (K_r) (Geological Society Engineering Group 1990)
$K_r = (\%SiO_2/60) / (\%SiO_2/102)+(\%Fe_2O_3/160)$

Silica-titania index (STI) (Jayawardena & Izawa, 1993)
$STI = (SiO_2/TiO_2)*100 / ((SiO_2/TiO_2)+(SiO_2/Al_2O_3)+(Al_2O_3/TiO_2))$

Alumina-titania Index (ATI) (Jayawardena & Izawa, 1993)
$ATI = (Al_2O_3/TiO_2)*100 / ((SiO_2/TiO_2)+(SiO_2/Al_2O_3)+(Al_2O_3/TiO_2))$

Gerrard (1992) provides following chemical weathering indices:

Silica-alumina ratio (SAR) = SiO_2/Al_2O_3
Silica-ferric oxide ratio (SFOR) = SiO_2/Fe_2O_3
Silica-sequioxide ratio (SSR) = $SiO_2/(Al_2O_3+Fe_2O_3)$
Alkali-alumina ratio (AAR) = $(K_2O+Na_2O)/Al_2O_3$
Alkali earth-alumina ratio (AEAR) = $(CaO+MgO)/Al_2O_3$
Calcic-magnesia ratio (CMA) = CaO/MgO
Potassic-sodaic ratio (PSR) = K_2O/Na_2O
Potassic-silica ratio (PSR) = K_2O/SiO_2

For the granite samples from the Lham Nah Creek, the weathering indices based on mineralogy do not show any distinct relationship with degree of weathering. Although chemical weathering indices like silica-sesquioxide ratio (K_r), Product Index (PI), Silica-alumina Ratio (SAR) and Silica-sequioxide Ratio (SSR) indicate an increasing trend and Weathering Potential Index (WPI) and Alkali Earth-alumina Ratio (AEAR) show decreasing trend with degree of weathering, the variations are not distinct. However, variation in Silica-ferric Oxide Ratio (SFOR) with degree of weathering is quite distinct as indicated in Figure 2. Therefore, it is concluded that the silica-ferric oxide ratio (SFOR) is an appropriate index to define the state of weathering in Khao Luang Mountain Range.

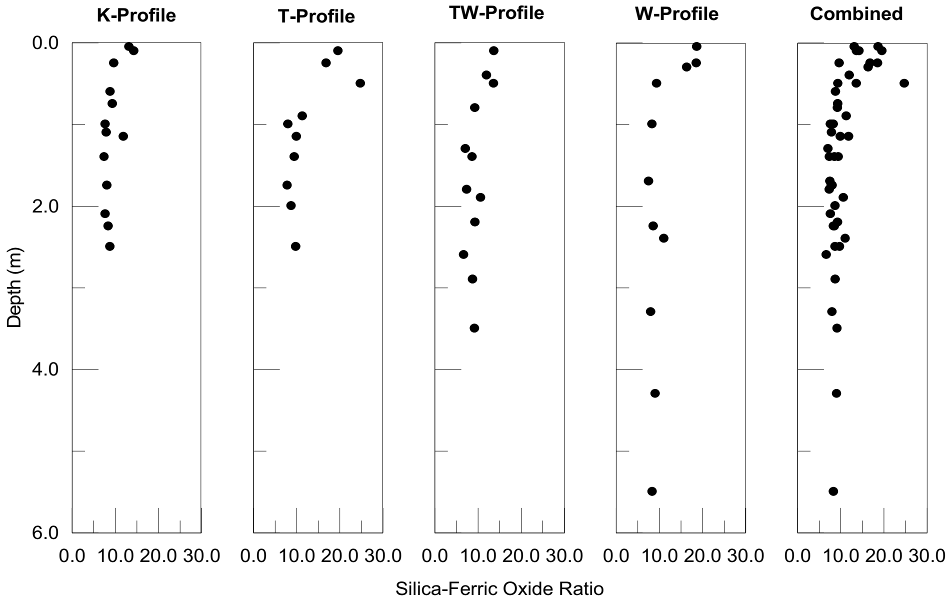

Figure 2. Variations in silica-ferric oxide ratio with depth/degree of weathering at four locations in the Lham Nah Creek Basin

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