

# Major and Trace Elements Geochemistry of Laterites from the Swarnagadde Plateau, Uttar Kannada District, Karnataka, India

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**Abstract** The laterite deposits of Swarnagadde plateau occurs in Uttar Kannada district of Karnataka state, forming low altitude flat topped laterite hills and plateaus adjoining part of Central Western Ghats, in the western continental margin of India. In this study, using geochemical techniques for calculation of relative weathering ( $\text{SiO}_2$  content), CIA and correlation coefficients, the effective factors in mobilization and redistribution of major and trace elements during lateritization processes across selected profile were considered. According to the  $\text{Al}_2\text{O}_3\text{-Fe}_2\text{O}_3\text{-SiO}_2$  ternary diagram of Schellmann [1] the limit of kaolinization on the tri-plot for the protolith of Swarnagadde plateau profile (granite/gneiss rock) is determined to occur at 68.22%  $\text{SiO}_2$  and gradual change from  $\text{SiO}_2$ -rich to  $\text{Fe}_2\text{O}_3$ -rich to  $\text{Al}_2\text{O}_3$ -rich compositions and of increasing degree of lateritization. The laterite samples were highly weathered with chemical index of alteration ca.98.92%, nearly complete loss of Na, Ca, Mg and K in the ferruginous zone. Fe mainly occurred as goethite, hematite, while Al mainly occurred as secondary clay minerals (kaolinite) and gibbsite below the ferruginous zone. On the basis of mineralogy and geochemistry, these deposits are grouped as aluminous laterites, ferruginous laterites and lithomargic clay. The major, trace elements and mineralogical characteristics of laterites, these were formed *in situ* by the alteration of parent rocks of granite/granitic gneiss compositions. The correlation coefficient patterns of several major and trace elements and their preferential enrichment have suggested that there is an influence of precursor rock on the distribution of trace elements. Significant depletion of base cations and Si, coupled with enrichment of Fe and Al, reveal that intense leaching of cations, kaolinization, desilication and ferruginization took place in lateritic deposits during weathering and lateritization.

**Keywords:** Swarnagadde, laterite, weathering, cations, aluminous

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## 1. Introduction

Chemical weathering of rocks is one of the major processes which modify the Earth's surface and is one of the major processes in the geochemical cycling of elements [2]. As a result, the mobilization and redistribution of elements in weathered products is much different from that of parent rocks [3,4]. The rate and nature of chemical weathering is controlled by various factors such as parent rock type, topography, climate and biological activities [5,6]. During chemical weathering the elements Al, Fe and Ti tend to combined with secondary minerals and retained in the weathering profile [7,8,9], on the other hand, the elements such as Na, K, Mg and Ca do not react with other elements and are removed in the percolating groundwater (lower pH) through the fissures and fractured zones. Kaolinite, gibbsite and other oxides are formed in these bleached or oxidized zones, because all dissolved salts are removed [10].

The behaviour of trace elements during weathering is complicated because these elements are affected by various processes such as dissolution of primary minerals, formation of secondary minerals, redox processes, transport of material, coprecipitation and ion exchange on various minerals [3,4,7,11,12,13,14]. Alkali and alkaline earth materials are easily removed from primary minerals [8]. On the contrary elements that are predominantly hosted in highly resistant minerals, such as Ti, Ta, Cr, Nb, Zr and Hf in granitic rocks are believed to be immobile [8,11]. Laterites are the product of intensive and long lasting tropical rock weathering which is intensified by the high rainfall and elevated temperatures, initially product of weathering are essentially kaolinised saprolite [1,15]. Thus the dominant process of laterite formation is the residual enrichment of iron and frequently of aluminium by removal of silica, alkalis and alkaline earth materials. This chemical alteration corresponds mineralogical with the formation of goethite, hematite, kaolinite and gibbsite with the relicts of partially dissolved quartz from the bulk of laterites. Laterites are formed from the leaching of

sedimentary, metamorphic, igneous and mineralized proto-ores which are predominantly iron and aluminium [16].

The mechanism of leaching involves acid dissolving the host mineral lattice, followed by hydrolysis and precipitation of insoluble oxides and sulphates of iron and aluminium. Oxidation is also another important aspect [3,17] of chemical weathering, ions like Fe and Mn are moderately soluble under reducing conditions and very insoluble under oxidizing conditions, and mobility of these elements depends to a large degree on the redox potential. This process occurs under high temperature conditions of humid tropical and sub-tropical monsoon climate and, an essential feature for the formation of laterite is the repetition of wet and dry seasons [18] which facilitates weathering processes. Most of the studies have been carried out on the weathering intensities from incipient to advanced degrees. The behaviour of major and minor elements during the development of laterites have been investigated [19,20,21], and relates the leaching and retention of a range of elements to mineral transformations in the principal components of weathering profile.

There is no geochemical investigations for major and trace elements of this laterite deposits were carried out so far. The purpose of this study is to investigate the chemical weathering of rocks, resulting into lateritization processes in one environmental setting. In this paper we focus mainly on mechanism and fractionation of major and trace elements, particularly as a function of weathering intensity, and the factors affecting the mobilization and redistribution of selected elements during the processes of lateritization at Swarnagadde plateau, Karnataka.

## 2. Geological Setting

The investigated area comprises the coastal margin of western peninsular India between 14°18' to 14°24' N and 74°24' to 74° 30' E of the India Toposheet No-47J/8 (Figure 1). The laterite deposits of Swarnagadde plateau occurs in Uttar Kannada district of Karnataka state, forming low altitude flat topped laterite hills and plateaux adjoining part of Central Western Ghats, in the western continental margin of India. The multiphase rift history that affected western India during Mesozoic has placed important constraints upon this morphotectonic evolution, and deep weathering effects that have contributed in the development and formation of lateritic terrain along the South Indian west coast probably began about 90 million years ago with the separation of India from Madagascar. The coastal lowlands of western India lying between the Arabian Sea and the foot of the Western Ghats escarpment are known as Konkan in Maharashtra, Kanara in Karnataka and Malabar in Kerala States. However, occurrence of these lateritic deposits as clusters of plateaux over large tracts of lowlands. The most widespread occurrences of laterites within the Western India have been recognized in a series of different geological-geomorphological settings, and are found in two distinct geomorphological zones: (i) capping the elevated basalt mesas of the Western Ghats, where they are developed upon the Deccan lavas [22,23,24] and (ii) an extensive, semi-continuous belt lying to the west of the main Western Ghats escarpment between Bombay and Mangalore capping the coastal plateaux of the outer Konkan plain [25].

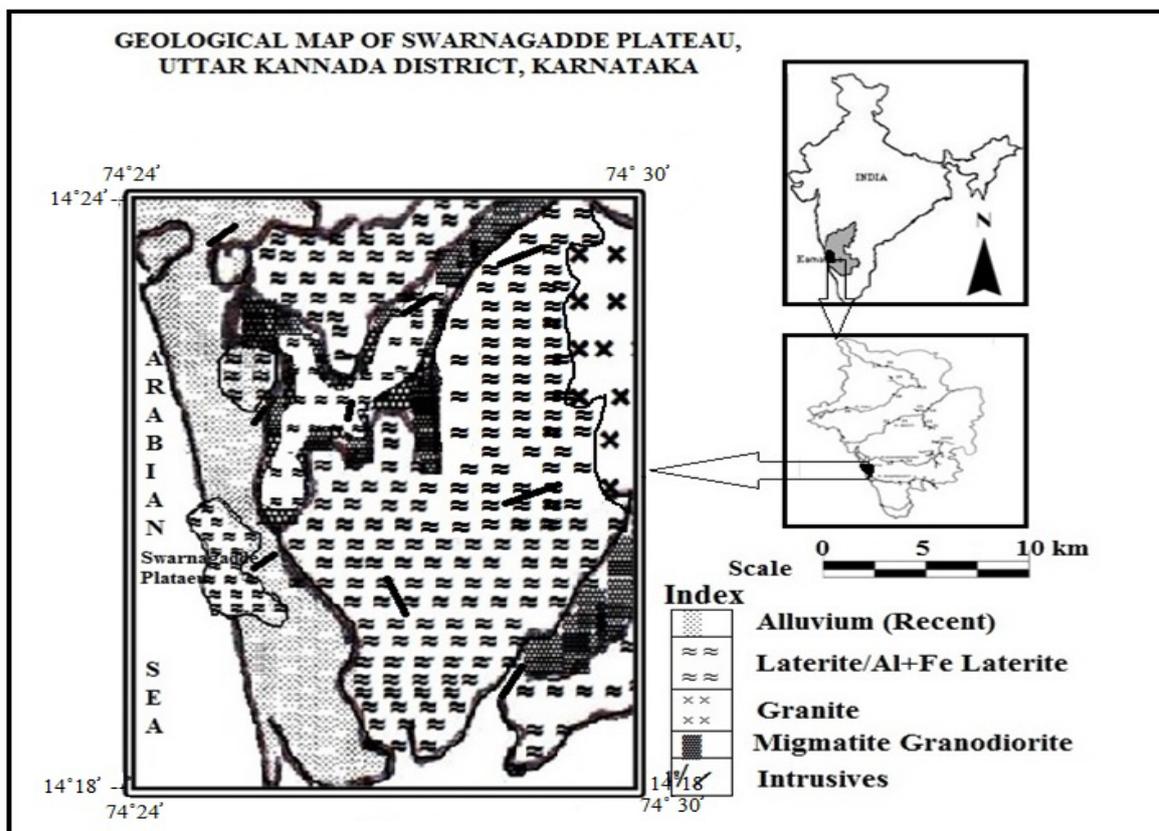


Figure 1. Generalized geological map of the study area

The Western Ghats escarpment is preceded by a ramp of dissected laterite-capped mesas which slope gently from altitude of ca. 180 to 200m in the east of the coastal plain, to ca. 80 to 100m adjacent to the coast. A second generation of laterite mesas is particularly prominent in estuarine regions and occupies a lower elevation of 60m-70m.

The study area is characterized by Precambrian crystalline rocks (Granites, Granitic gneisses and Schists), laterites and basic dykes. The oldest rock of the study area is granitic gneiss and these are predominantly of tonalite in nature and are comparable to similar early Precambrian granitic gneiss of other shield areas of the world. Granites/granitic gneisses cover major portion of the coastal tract, which is the North-Western coastal continuation of peninsular gneisses or Northern continuation of South Kanara gneisses/granites. The gneisses form prominent hills and headlands along the coasts, however, the granites are present as patches within gneisses.

### 3. Materials and Methods

In order to understand geochemical characteristics of major and trace elements of laterite deposits from

Swarnagadde plateau, Uttar Kannada district, a complete weathering profile was selected. Geological field mapping was carried out between April and May, 2010 and 2011, nearly 14 representative samples were collected from different profiles (at the interval of 0.25 to 0.5-m at surface and 1.0 m) in vertical section of laterite mining quarry (Figure 2). Sampling of weathered crust began from the protolith (parent rock) and the interval within profile was determined based on the lithological, mineralogical and physical characters. The colour of the weathered material is brown to reddish brown or brown to yellowish brown which is mainly due to hard bed rock.

Determination of chemical composition, fourteen samples were selected and analyzed by using inductively coupled plasma optical emission spectroscopy (ICP-OES for major and minor oxides) and inductively coupled plasma mass spectroscopy (ICP-MS for trace and rare earth elements) with fusion opening (lithium borate) and, with 4-acid digestion. Loss on ignition (LOI) values was measured by weight reduction of the samples after 1 hr heating at 1,000°C. Detection limit for SiO<sub>2</sub>, Fe<sub>2</sub>O<sub>3</sub>, CaO, MgO, Na<sub>2</sub>O, K<sub>2</sub>O, TiO<sub>2</sub>, P<sub>2</sub>O<sub>5</sub> are 0.01 wt%; Cr<sub>2</sub>O<sub>3</sub> 0.002 wt%. Detection limit for trace elements is 0.5 ppm and for rare earth elements 0.1 ppm. The results of the chemical analysis are presented in the Table 1.

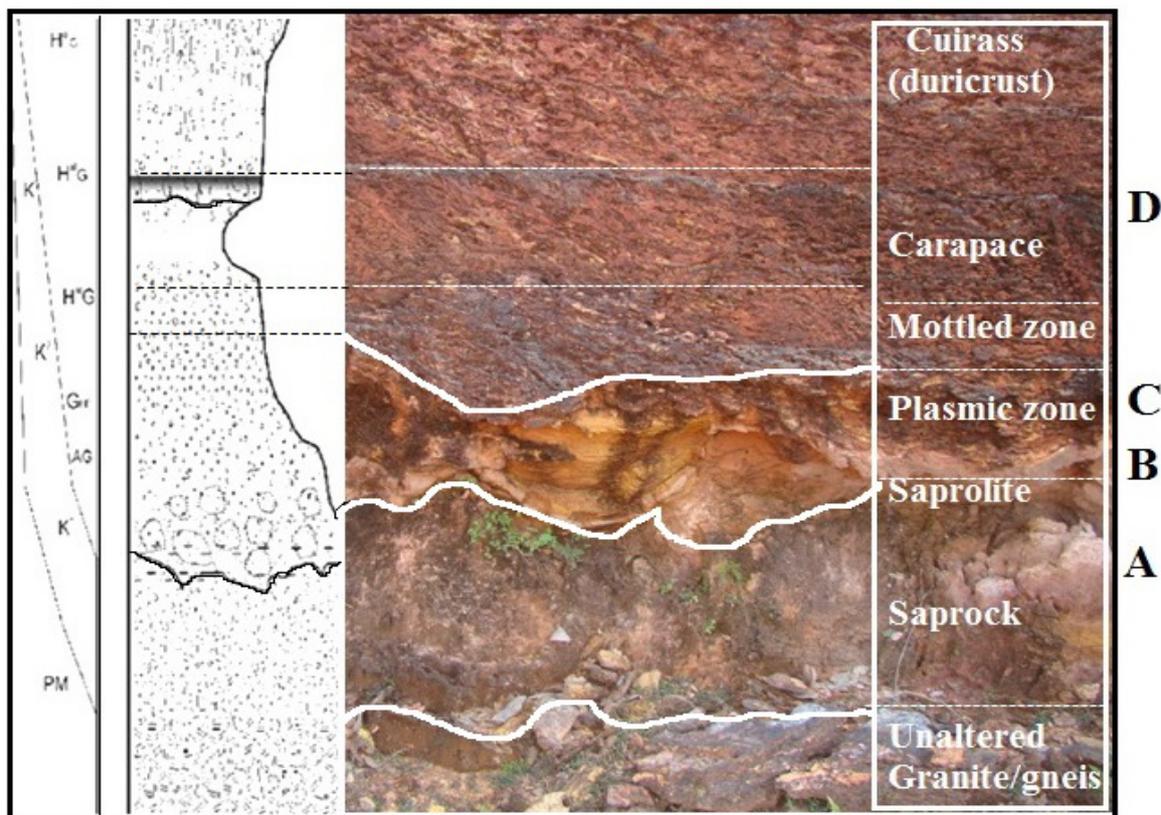


Figure 2. Field photograph of complete weathered lateritic profile of the study area showing different zones from protolith to top duricrust

## 4. Results and Discussion

### 4.1. Geochemistry

The results of chemical composition of the lateritic deposits across the studied profile and granitic parent rocks shows SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub> domain (Table 1). The

silica content ranges from 11.13 to 58.29%, decreasing from the base parent granitic rock (71.71 to 73.26%) towards the top of the weathered profile, which corresponds to the transition from the ferruginous/aluminous crust to the covering soil (Figure 2). The content of Al/Fe reflects the variable kaolinite content, which is more at the base and absent near the top of the profile indicating formation of secondary minerals with the increase intensity of

weathering. The concentration of  $\text{Fe}_2\text{O}_3$  content displays an inverse behaviour compared to  $\text{SiO}_2$ , ranges from 2.53 to 47.11% (2.45 to 2.89%), which is typical of lateritic profile and is higher than in the aluminous crust. The  $\text{Al}_2\text{O}_3$  content is slightly enriched comparatively  $\text{Fe}_2\text{O}_3$

and ranges from 22.14 to 48.43% (14.26 to 14.91%) increasing upward over the lithomargic clay horizon. Loss on ignition (LOI) ranges from 10.25 to 27.55% of the weathering products, and LOI in the lower sections is generally higher than the upper section of the profile.

**Table 1. Concentration values of Major, Minor (wt %) and Trace (ppm) elements in samples taken from the lateritic deposit of the study area.**

Sample	L-8/1	L-8/2	L-8/3	BS/05	BS/10	BS/07	BS/06	BS/02	BS/25	BS/27	BS/29	GN/3T	GN/2M	GN/1B
Depth (m)	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5
$\text{SiO}_2$ (%)	12.76	18.45	25.3	14.22	11.13	12.67	11.9	13.06	48.17	43.75	58.29	71.71	72.06	73.26
$\text{Al}_2\text{O}_3$	23.66	22.14	24.12	48.43	36.75	42.59	39.67	44.05	36.14	38.31	24.18	14.91	14.87	14.26
$\text{Fe}_2\text{O}_3$	47.11	44.17	35.66	7.06	27.86	17.46	22.66	14.86	2.53	4.52	2.97	2.89	2.48	2.45
$\text{TiO}_2$	1.12	1.7	1.59	1.81	1.78	1.8	1.79	1.8	1.38	1.15	1.58	0.26	0.24	0.25
MgO	0.13	0.13	0.09	0.01	0.01	0.02	0.02	0.02	0.37	0.59	0.68	1.02	1.01	0.97
CaO	0.07	0.06	0.08	0.05	0.07	0.06	0.07	0.06	0.05	0.03	0.05	0.45	0.7	0.79
$\text{K}_2\text{O}$	0.21	0.07	0.24	0.01	0.03	0.02	0.02	0.02	0.24	0.37	0.31	1.26	1.2	1.12
$\text{Na}_2\text{O}$	0.01	0.01	0.03	0.01	0.02	0.2	0.02	0.02	0.06	0.05	0.11	4.24	5.21	5.03
MnO	0.01	0.01	0.03	0.17	0.15	0.16	0.14	0.12	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
$\text{P}_2\text{O}_5$	0.86	0.07	0.14	0.13	0.14	0.13	0.13	0.13	0.56	0.13	0.17	0.05	0.07	0.08
$\text{Cr}_2\text{O}_3$	0.18	0.07	0.07	0.12	0.1	0.11	0.11	0.11	0.12	0.09	0.1	0.06	<0.05	<0.05
LOI	13.51	12.76	12.21	27.55	21.41	24.48	22.94	25.25	10.25	10.73	11.65	2.69	1.63	1.28
Total	99.63	99.64	99.55	99.57	99.55	99.54	99.55	99.54	99.88	99.74	100.09	99.54	99.48	99.48
CIA	98.47	99.08	98.16	99.74	99.48	98.92	99.55	99.63	97.98	98.57	97.56	61.95	57.15	56.64
Rw	0.18	0.28	0.42	0.26	0.17	0.21	0.19	0.22	1.31	1.02	2.15	4.03	4.15	4.38
Rel $\text{SiO}_2$	15.28	21.77	29.73	20.4	14.7	17.43	16.03	18.15	60.57	50.53	68.22	80.11	80.59	81.43
Ag (ppm)	<0.5	0.88	0.93	1.49	1.46	1.48	1.47	1.48	1.86	1.65	1.57	<0.5	0.62	0.58
Co	9.42	3.14	4.88	40.79	21.98	31.38	26.68	33.73	50.98	45.12	42.95	4.86	3.43	2.68
Cr	123.2	47.9	47.9	82.1	71.85	76.98	74.41	78.26	102.63	75.32	78.71	41.1	<0.5	<0.5
Cs	1.09	<0.1	0.76	0.14	0.4	0.27	0.34	0.24	0.18	0.11	0.13	0.47	0.4	0.35
Cu	52.1	25.95	50.82	19.43	31.45	25.44	28.45	23.94	24.28	17.25	18.34	6.7	4.87	4.18
Ga	28.95	30.09	27.36	64.87	54.92	59.9	57.41	61.14	81.09	59.45	62.16	23.15	20.43	16.52
Hf	2.84	2.74	2.35	5.11	4.4	4.75	4.57	4.84	6.39	4.23	4.67	1.4	1.14	1.05
Mo	13.51	13.23	3.27	6.73	8.25	7.49	7.87	7.3	8.41	7.54	7.13	0.85	0.78	<0.5
Nb	8.77	13.39	10.68	21.57	19.1	20.33	19.72	20.64	26.97	23.12	22.35	2.52	1.9	1.71
Ni	101.69	88.89	125.98	49.77	45.4	47.59	46.49	48.13	62.21	42.62	46.19	9.72	3.18	2.78
Pb	27.58	18.15	18.81	34.51	28.27	31.39	29.83	32.17	43.14	28.61	31.56	10.31	7.85	7.38
Rb	11.5	2.52	10.06	1.85	6.97	4.41	5.69	3.77	2.31	1.23	1.54	43.68	38.97	33.38
Sb	9.28	2.13	1.95	2.83	4.1	3.46	3.78	3.31	3.54	2.33	2.58	<0.5	<0.5	<0.5
Sc	28.86	20.5	22.85	19.59	27.46	23.52	25.49	22.54	24.48	16.54	18.06	2.17	1.57	1.33
Se	2.87	3.43	2.07	1.04	1.99	1.52	1.75	1.4	1.3	0.99	1.01	<0.5	<0.5	<0.5
Sn	<0.5	<0.5	<0.5	1.76	1.65	1.52	1.78	1.45	2.2	1.32	1.54	0.71	<0.5	<0.5
Sr	17.58	13.45	14.87	32.37	31.72	32.04	31.88	32.12	40.46	29.73	31.05	255.37	325.34	275.37
Ta	0.59	0.88	0.81	1.38	1.23	1.3	1.27	1.32	1.72	1.12	1.25	<0.5	<0.5	<0.5
Th	13.71	11.13	10.25	25.37	22.54	23.95	23.25	24.31	31.71	21.43	23.4	3.2	2.9	2.72
U	6.08	2.16	2.2	4.73	4.78	4.76	4.77	4.75	5.92	2.32	3.53	1	0.65	<0.5
W	1.35	1.08	0.84	2.09	1.91	2	1.96	2.03	2.62	2.02	2.06	<0.5	<0.5	<0.5
Y	4.73	3.82	5.59	7.17	7.09	7.13	7.11	7.14	8.97	6.19	6.68	2.87	3.96	3.65
Zn	41.57	17.58	34.31	34.39	33.06	33.73	33.4	33.89	42.99	38.85	36.62	67.99	79.64	47.17
Zr	97.34	102.26	89.76	194.77	166.38	180.58	173.48	184.13	243.47	98.35	146.56	63.36	52.21	44.28

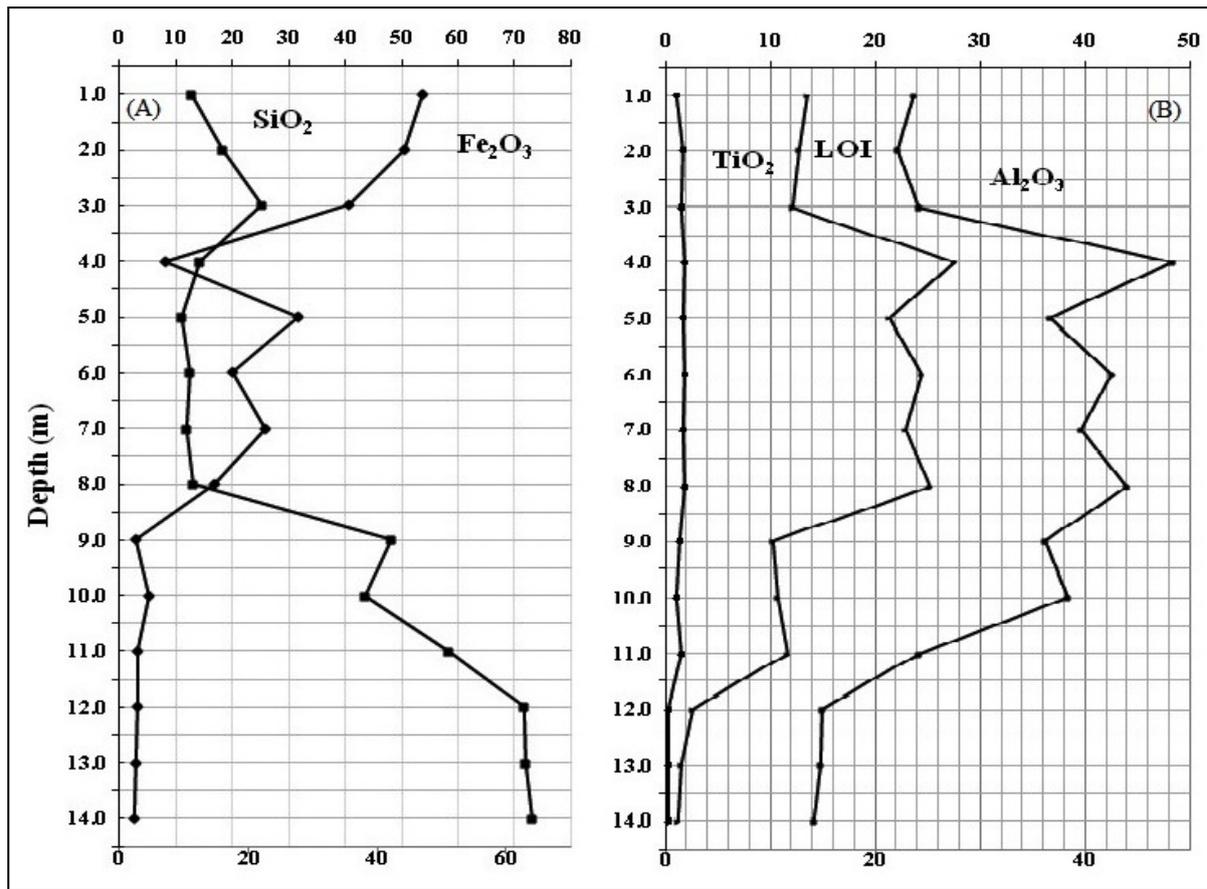


Figure 3. Distribution of major elements of the laterite profile. (A) SiO<sub>2</sub> and Fe<sub>2</sub>O<sub>3</sub>. (B) TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and Loss on Ignition

Both Al<sub>2</sub>O<sub>3</sub> and LOI oscillates positively between 3.0 and 5.0 m reflecting weak gibbsite enrichment (Figure 3 A & Figure 3 B), since Al<sub>2</sub>O<sub>3</sub> and LOI are associated with gibbsite, kaolinite and Al-goethite abundance. The analytical data shows that concentrations of components such as CaO, Na<sub>2</sub>O, MgO and K<sub>2</sub>O in the lateritic deposits in comparison with those of the granitic (basement) parent rocks are very low. The values are comparable with those presented by Nesbitt and Wilson [9] for advanced and extreme weathering process. TiO<sub>2</sub> and P<sub>2</sub>O<sub>5</sub> contents are higher than the parent rocks, ranging from 1.12 to 1.81% and 0.07 to 0.86% respectively.

Major oxides like Na<sub>2</sub>O, K<sub>2</sub>O, MgO and CaO show significant correlation with SiO<sub>2</sub>, on the contrary major oxides such as Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> show negative correlation with SiO<sub>2</sub>. Elements such as Al, Fe and Ti are immobile and susceptible to chemical weathering processes. Their oxides reflect negative correlation with SiO<sub>2</sub>. In contrast, oxides of mobile elements such as Na, Mg, K and Ca show positive correlations with SiO<sub>2</sub>. All most all the laterites have similar ratios of SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub>/Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> (Figure 4). Suggesting that, they were possibly derived from the same source of materials.

#### 4.2. Discussion: Degree of lateritization

The degree of alteration/lateritization occurring within a lateritic profile can be achieved using major oxide data for the weathering products, and compares them to that of the protolith (parent rock) composition through the use of SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub> triangular plot (Figure 5) [1,15].

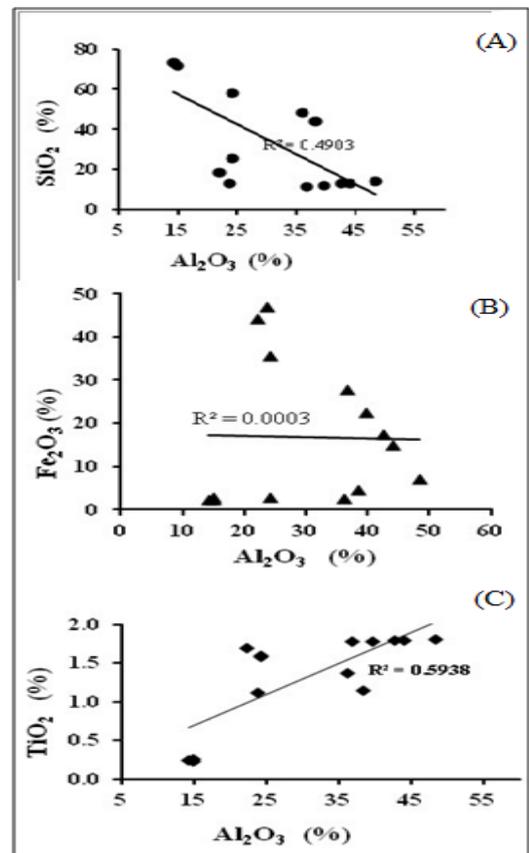
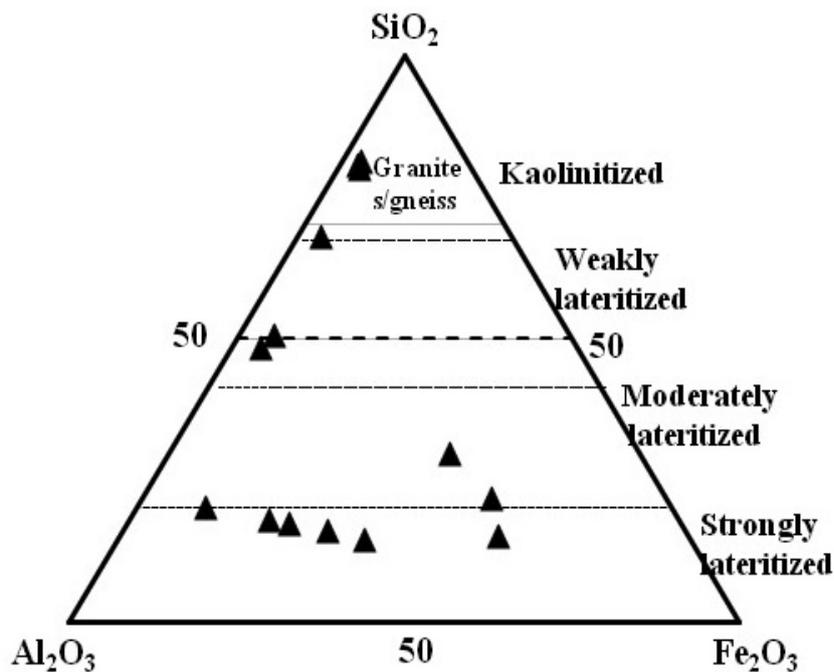


Figure 4. Scatter plots of major oxides in the lateritic deposits (A) SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>. (B) Fe<sub>2</sub>O<sub>3</sub>/Al<sub>2</sub>O<sub>3</sub> and (C) TiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub>

**Table 2. Correlation coefficients of major and trace elements of the laterite deposits of the study area**

	Si	Al	Fe	Ti	Mg	Ca	K	Na	Mn	P	Cr	Co	Cu	Ga	Hf	Li	Mo	Nb	Ni	Pb	Sr	Zn	Zr
Si	1	-0.62	-0.71	-0.64	0.86	0.65	0.77	0.79	-0.49	-0.20	0.18	-0.16	-0.25	-0.41	-0.54	0.45	-0.66	-0.52	-0.42	-0.54	0.63	0.63	-0.63
Al	-0.62	1	-0.10	0.68	-0.60	-0.53	-0.80	-0.63	0.90	0.01	0.13	0.74	-0.08	0.82	0.85	-0.39	0.46	0.81	0.00	0.70	-0.49	-0.55	0.85
Fe	-0.71	-0.10	1	0.23	-0.55	-0.39	-0.27	-0.48	-0.58	0.28	-0.29	-0.41	0.42	-0.17	-0.03	-0.33	0.45	-0.01	0.59	0.10	-0.40	-0.32	0.04
Ti	-0.64	0.68	0.23	1	-0.74	-0.67	-0.88	-0.80	0.27	-0.04	0.05	0.41	0.43	0.55	0.72	-0.45	0.39	0.69	0.39	0.51	-0.65	-0.59	0.75
Mg	0.86	-0.60	-0.55	-0.74	1	0.51	0.82	0.77	-0.53	-0.16	0.13	-0.20	-0.35	-0.41	-0.56	0.45	-0.48	-0.52	-0.51	-0.57	0.43	0.59	-0.66
Ca	0.65	-0.53	-0.39	-0.67	0.51	1	0.64	0.84	-0.10	-0.20	0.23	-0.41	-0.29	-0.48	-0.60	0.06	-0.52	-0.63	-0.51	-0.58	0.95	0.58	-0.57
K	0.77	-0.80	-0.27	-0.88	0.82	0.64	1	0.85	-0.60	-0.16	-0.12	-0.52	-0.13	-0.65	-0.77	0.50	-0.62	-0.76	-0.31	-0.62	0.62	0.78	-0.79
Na	0.79	-0.63	-0.48	-0.80	0.77	0.84	0.85	1	-0.09	-0.26	-0.07	-0.46	-0.33	-0.55	-0.69	0.24	-0.61	-0.73	-0.60	-0.71	0.83	0.72	-0.65
Mn	-0.49	0.90	-0.58	0.27	-0.53	-0.10	-0.60	-0.09	1	-0.27	0.33	0.90	-0.48	0.90	0.80	-0.28	0.20	0.76	-0.70	0.66	-0.07	-0.34	0.83
P	-0.20	0.01	0.28	-0.04	-0.16	-0.20	-0.16	-0.26	-0.27	1	-0.05	0.16	0.05	0.15	0.19	0.17	0.52	0.19	0.31	0.38	-0.19	0.01	0.06
Cr	0.18	0.13	-0.29	0.05	0.13	0.23	-0.12	-0.07	0.33	-0.05	1	0.04	-0.26	-0.18	-0.24	-0.07	-0.17	-0.19	-0.33	-0.29	-0.13	-0.43	-0.30
Co	-0.16	0.74	-0.41	0.41	-0.20	-0.41	-0.52	-0.46	0.90	0.16	0.04	1	-0.17	0.91	0.85	-0.17	0.40	0.86	-0.08	0.80	-0.37	-0.27	0.71
Cu	-0.25	-0.08	0.42	0.43	-0.35	-0.29	-0.13	-0.33	-0.48	0.05	-0.26	-0.17	1	-0.16	0.03	-0.11	-0.14	0.00	0.71	0.13	-0.27	0.20	0.06
Ga	-0.41	0.82	-0.17	0.55	-0.41	-0.48	-0.65	-0.55	0.90	0.15	-0.18	0.91	-0.16	1	0.97	-0.43	0.58	0.96	-0.06	0.84	-0.42	-0.37	0.89
Hf	-0.54	0.85	-0.03	0.72	-0.56	-0.60	-0.77	-0.69	0.80	0.19	-0.24	0.85	0.03	0.97	1	-0.43	0.63	0.98	0.12	0.87	-0.54	-0.44	0.95
Li	0.45	-0.39	-0.33	-0.45	0.45	0.06	0.50	0.24	-0.28	0.17	-0.07	-0.17	-0.11	-0.43	-0.43	1	-0.44	-0.41	0.07	-0.09	0.02	0.41	-0.44
Mo	-0.66	0.46	0.45	0.39	-0.48	-0.52	-0.62	-0.61	0.20	0.52	-0.17	0.40	-0.14	0.58	0.63	-0.44	1	0.65	0.13	0.61	-0.51	-0.56	0.56
Nb	-0.52	0.81	-0.01	0.69	-0.52	-0.63	-0.76	-0.73	0.76	0.19	-0.19	0.86	0.00	0.96	0.98	-0.41	0.65	1	0.16	0.86	-0.57	-0.49	0.88
Ni	-0.42	0.00	0.59	0.39	-0.51	-0.51	-0.31	-0.60	-0.70	0.31	-0.33	-0.08	0.71	-0.06	0.12	0.07	0.13	0.16	1	0.32	-0.50	-0.16	0.11
Pb	-0.54	0.70	0.10	0.51	-0.57	-0.58	-0.62	-0.71	0.66	0.38	-0.29	0.80	0.13	0.84	0.87	-0.09	0.61	0.86	0.32	1	-0.50	-0.31	0.80
Sr	0.63	-0.49	-0.40	-0.65	0.43	0.95	0.62	0.83	-0.07	-0.19	-0.13	-0.37	-0.27	-0.42	-0.54	0.02	-0.51	-0.57	-0.50	-0.50	1	0.60	-0.51
Zn	0.63	-0.55	-0.32	-0.59	0.59	0.58	0.78	0.72	-0.34	0.01	-0.43	-0.27	0.20	-0.37	-0.44	0.41	-0.56	-0.49	-0.16	-0.31	0.60	1	-0.45
Zr	-0.63	0.85	0.04	0.75	-0.66	-0.57	-0.79	-0.65	0.83	0.06	-0.30	0.71	0.06	0.89	0.95	-0.44	0.56	0.88	0.11	0.80	-0.51	-0.45	1



**Figure 5. Triangular plot of SiO<sub>2</sub>-Fe<sub>2</sub>O<sub>3</sub>-Al<sub>2</sub>O<sub>3</sub> showing degree of lateritization (after Schellmann, 1986)**

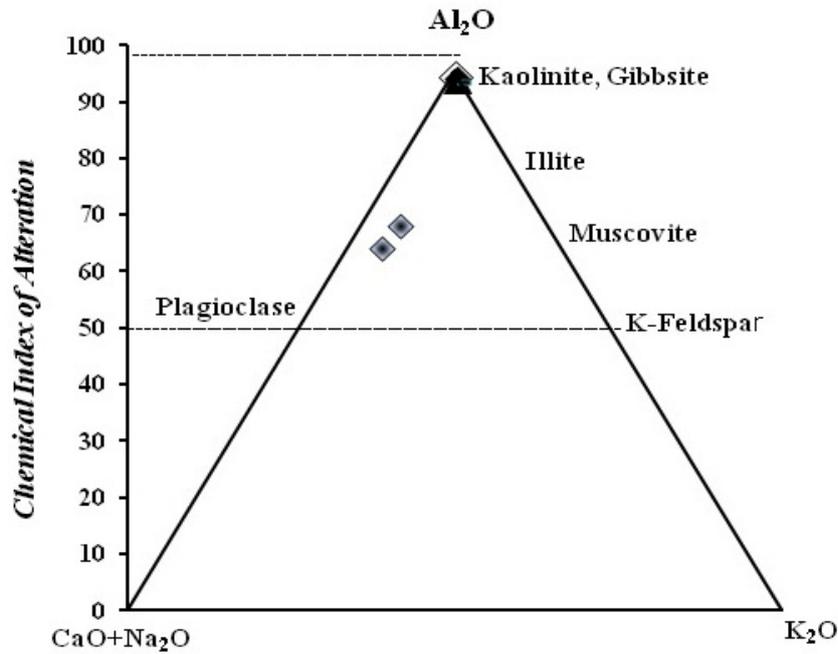


Figure 6. A-CN-K ternary diagram (modified from Nesbitt and Young, 1982; Fedo et al., 1995) showing weathering trends of laterite profile

This method determines three levels of lateritization, weak, moderate and strong on the basis of the decreasing relative  $\text{SiO}_2$  contents. The limit of Kaolinization is determined by assuming the aluminium available in the protolith would be first converted to kaolinite through the combination with the available silica, and that any further weathering (i.e., silica loss) beyond this condition therefore marks the stage of the laterite.

The samples indicate that the deep weathering profiles are thought to develop through the downward progression of weathering front, and the associated expansion of the saprolitic, mottled and lateritic zones with weak lateritization to strong lateritization of the study area (Figure 5). According to the  $\text{Al}_2\text{O}_3\text{-Fe}_2\text{O}_3\text{-SiO}_2$  ternary diagram of Schellmann [1] the limit of kaolinization on the tri-plot for the protolith of Swarnagadde plateau profile (granite/gneiss rock) is determined to occur at 68.22%  $\text{SiO}_2$  and gradual change from  $\text{SiO}_2$  - rich to  $\text{Fe}_2\text{O}_3$ -rich to  $\text{Al}_2\text{O}_3$ -rich compositions (Figure 5) and of increasing degree of lateritization.

## 4.2. Chemical Weathering

### Chemical Index of Alteration (CIA)

Chemical changes during incipient to moderate stages of weathering processes, Ca, Na, Mg and K of the parent rocks are relatively mobile and are easily leached out, resulting in a depletion of these elements and enrichment of immobile elements. Chemical weathering of minerals and mobility of major elements, the (CIA) Chemical Index of Alteration [26] increases from the parent rock upward to the surface soil, suggesting the increasing of chemical weathering, accompanied by the conversion of more and more feldspar minerals to clay minerals, because it not only includes potassium in its formation, but also combines potassium with other alkali and alkaline earth elements. The CIA is interpreted as a measure of the extent of conversion of feldspars (upper crust) to clays such as kaolinite [27,28,29,30], it has been used in

numerous paleosol studies [31]. The extent of weathering profile samples have been calculated using the molecular proportion of the major element oxides to alkaline elements. In doing so, stoichiometric changes during weathering are reflected in the index value.

$$\text{CIA} = \left[ \frac{(\text{Al}_2\text{O}_3)}{(\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})} \right] \times 100$$

(molar basis)

The lateritic samples have an average CIA value of 97.56, ranging from 61.95 to 99.92, with the highest CIA values in ferruginous laterites. This indicates that the weathering of the parent rocks resulted in more depletion of the labile alkalis and alkaline earth materials in ferruginous laterites than aluminous laterites. The CIA values above 90%, reflecting extreme weathering conditions. Samples from the weathering profile of the study area are plotted using  $\text{Al}_2\text{O}_3\text{-(CaO+Na}_2\text{O)-K}_2\text{O}$ -(A-CN-K) ternary plot (Figure 6), which demonstrates alteration trends in major element composition and minerals during the chemical weathering.

The A-CN-K triangular diagram describes the consequence of chemical weathering of the upper crust where plagioclase and K-feldspar are dissolved, causing depletion of Ca, Na and K and enrichment of Al [9,29]. As weathering progresses, the samples are and CIA value reaches above 90, plagioclase and K-bearing minerals (biotite, illite and K-feldspars) would be decomposed with further development of weathering and, with the releasing of K at the  $\text{Al}_2\text{O}_3$  apex, kaolinite, halloysite and gibbsite are the predominant clay minerals. In the studied weathering profile, most regolith samples were highly weathered, and the plots cluster closely at  $\text{Al}_2\text{O}_3$  apex, which reflects the presence of phyllosilicate clay minerals as main mineralogical components, suggesting an extensive weathering of source rock, this is consistent with the CIA interpretation. Corresponding with the variations in major elements, as the weathering progresses, percentage of clay minerals and the ratios

of quartz to feldspar and K-feldspar to plagioclase increases, and the mineral constituents of a weathering profile is determined to a large extent with the intensity of weathering.

### 4.3. Trace Elements

Distribution pattern of soluble trace elements, such as Rb and Sr in laterite profile indicate that those of soluble major elements such as Ca and Na, or Mg and K. The geochemical distribution of Sr to that of Ca; strontium always decreases with increasing alteration of the rocks, size of Sr cause to more readily exchanged on to clays than Ca [32]. Insoluble trace elements, such as Zr, Hf and Th show that these elements were at least with Ti,

essentially immobile in all parts of the profile. These observations agree vary well with predicted mobilities of those elements [11]. The geochemical distribution pattern of Nb, Sc and Ta shows that these elements are rather immobile during weathering, similar to those observations for various rock-types [11]. Correlation coefficients always show that  $\text{TiO}_2$  has strong positive correlation with high field strength elements (HFSE) Zr, Hf, Nb and Ta (Figure 7A, Figure 7B, Figure 7C, Figure 7D, Figure 7E and Figure 7F). Strong positive correlations also exist between Zr and Hf and between Nb and Ta (Figure 7 E and Figure 7F). Similarly, these analyses reflect that elements such as Zr and Co show strong positive correlation with Hf, Nb, Pb and Zr and Nb, Pb, Hf and Ga respectively (Table 2).

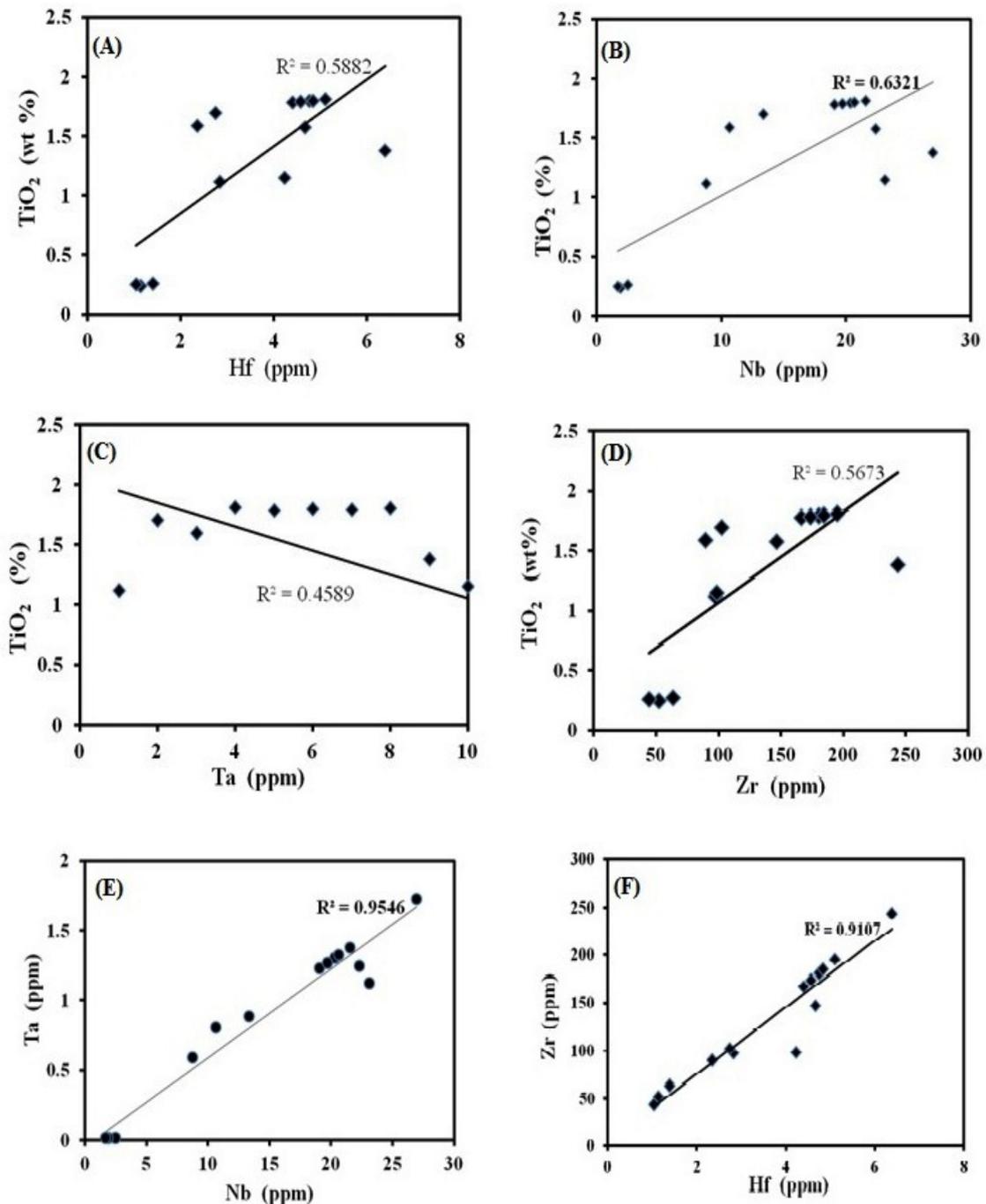


Figure 7. Variation diagrams showing correlations between trace elements in the studied laterite profile

## 5. Conclusion

The laterites and protolith of the study area shows varying concentrations of  $Al_2O_3$  (14.26-48.43%),  $SiO_2$  (11.9-73.26%),  $Fe_2O_3$  (2.45-47.11%) and  $TiO_2$  (0.26-1.81%), however, the amounts of  $Na_2O$  and  $K_2O$  are enriched in basement rock and gradual depletion towards top of the weathering profile suggests that highly mobile nature of these elements leaching with the percolating groundwater. Major mineralogical changes during weathering of granite/granitic gneiss are represented by feldspar into montmorillonite to illite to kaolinite, halloysite to bauxite. Gibbsite, quartz and kaolinite prevail in the residual lateritic profile despite the temperature climatic setting. Geochemical elements that are remained immobile during incipient to moderate stages of weathering were, Fe, Al, Zr, Hf, Th, Nb and Sc. However, Hf and Zr were the only elements that should no mobility under extreme alteration stages. Elements that are lost during moderate weathering were Na, Ca, K, Mg, Si and Sr, because elements lost were mainly derived from leachable minerals such as feldspars, micas and apatites. On the basis of mineralogy and geochemistry, these deposits are grouped as aluminous laterites, ferruginous laterites and lithomargic clay. The major, trace elements and mineralogical characteristics of laterites, these were formed *in situ* by the alteration of parents rocks of granite/granitic gneiss compositions.

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