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Degree of Lateritisation and Quantifying Weathering Intensity of Laterites from Swarnagadde Plateau, Karnataka.

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Abstract: 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. 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. Weathering is a combination of processes caused by mechanical, chemical and biological disintegration of a rock upon its interaction with the atmosphere. Significantly, the scheme recognises the importance of the nature of the protolith upon the composition of the weathering product; it also requires that the weathering products are entirely the result of *in situ* alteration processes. Using a SiO_2-Al_2O_3-Fe_2O_3 ternary diagram, four stages of alteration are recognised in the lateritisation process: (a) kaolinitisation, (b) weak lateritisation, (c) moderate lateritisation, and (d) strong lateritisation. The behaviour of major and minor elements during the development of laterites have been suitably summarised and relates the leaching and retention of a range of elements to mineral transformations in the principal horizons of the weathering profile.

Keywords: Weathering, Kaolinisation, Laterites, Minerals, Development.

I. INTRODUCTION

Laterites and aluminous laterites are the residual products mainly derived from a wide variety of parent rocks by intense chemical weathering under strongly oxidizing and leaching conditions of the area. 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 [5]. As a result, the mobilization and redistribution of elements in weathered products is much different from that of parent rocks [25, 27]. The rate and nature of chemical weathering is controlled by various factors such as parent rock type, topography, climate and biological activities [13, 4].

During chemical weathering the elements Al, Fe and Ti tend to combined with secondary minerals and retained in the weathering profile [9, 21, 20], 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 [37].

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, and transport of material, co-precipitation and ion exchange on various minerals [16, 25, 9, 14, 27, 10, and 15]. Alkali and alkaline earth materials are easily removed from primary minerals [20]. 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 [10, 20].

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 [30, 31]. 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, heamatite, kaolinite and gibbsite with the relicts of partially dissolved quartz from the bulk of laterites (Fig 1).

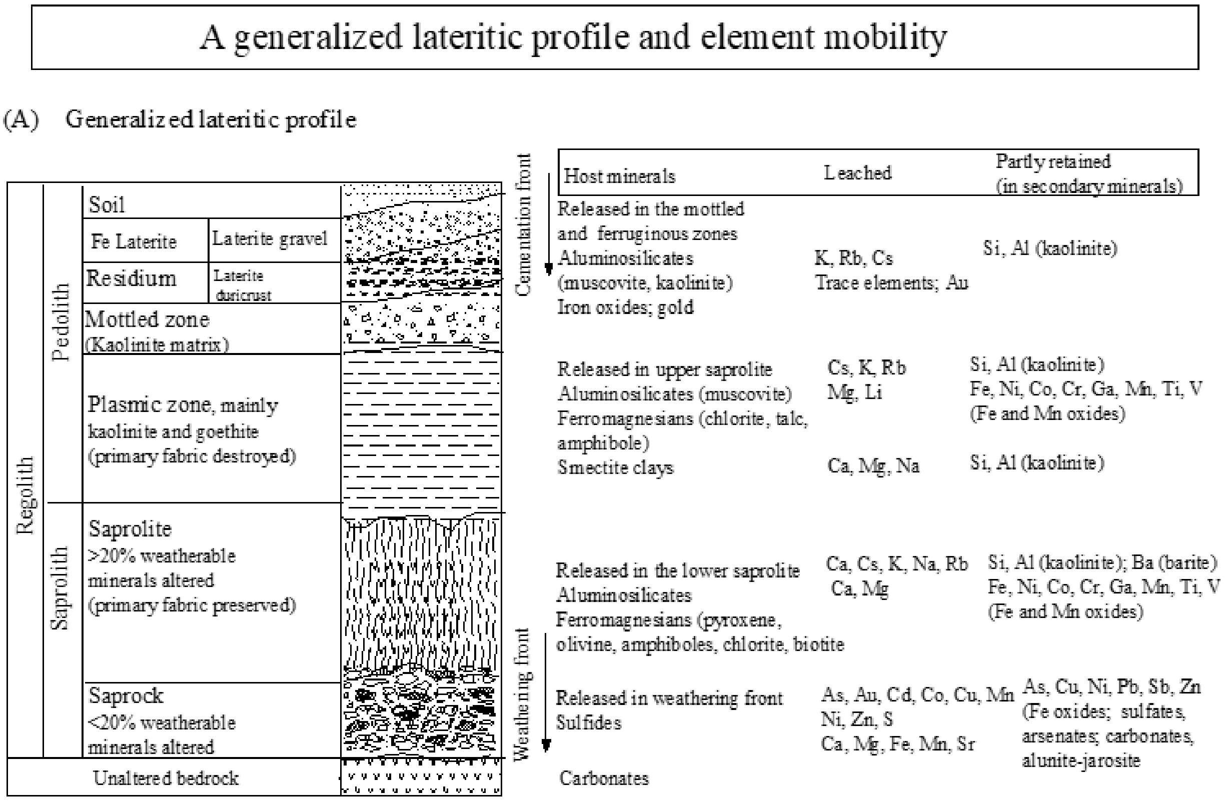

Fig 1: A generalized lateritic profile development and element mobility in the Swarnagadde plateau.

II. GEOLOGICAL BACKGROUND

The laterites and granitic gneisses comprise the study area. These are exposed at the base and along the northern and eastern scarp regions of the plateau that lies within Latitude 74° 24´ to 74° 30´ E and Longitude 14° 18´ to 14° 24´ N at the south western margin of the Peninsular region. Nevertheless, excellent exposures occur about 5 km south and south-east of Chandavara village. On the other hand, exfoliation or scaling is the most common and prominent feature noticed in the relatively large exposed outcrops of granitic gneisses.

These granitic gneisses appear in various shades of grey to pink, are fine to medium grained and possess a gneissic to massive texture. Locally there are coarse-grained, mineralogically similar bodies with sharp to gradational contacts. In part, the gneiss exhibits a salt and pepper texture and is mesocratic. The leucocratic variety is light grey to pink and locally possesses mafic lenses, pods and streaks as inclusions. Quartzo-feldspathic pegmatite veins and irregular bodies are common in the leucocratic granitic gneiss. In the study area, the mafic to felsic constituents differs considerably from out crop to out crop. The lighter leucocratic varieties have some potash feldspars and may locally be more abundant than plagioclase.

III. MATERIALS AND METHODS

Both field and laboratory investigations were undertaken as part of the present investigation. Field studies included-Preparation of geomorphic map of the study area and map showing the distribution of laterite (scale 1:50,000). Field checking of compiled geological map of the study area (scale 1:50,000). Laterite profile description and systematic collection of samples from the profiles developed over basement litho-units.

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_2, Fe_2O_3, CaO, MgO, Na_2O, K_2O, TiO_2, P_2O_5 are 0.01 wt%; Cr_2O_3 0.002 wt%. Detection limit for trace elements is 0.5 ppm and for rare earth elements 0.1 ppm.

IV. RESULTS AND DISCUSSION

A.1: Weathering of Granite gneiss and development of weathering sequence.

In granitic gneiss or granites, feldspars (plagioclase and alkali-feldspar) and micas are more prone to weathering than quartz [22]. Weathering is a combination of processes caused by mechanical, chemical and biological disintegration of a rock upon its interaction with the atmosphere. The physical weathering of the rock creates fracturing while chemical weathering changes mineral composition of the rock and biological weathering is responsible for both effects [36]. The sequences in which minerals of rock are altered reflect the stability of the minerals, which represent the crystallization temperature (Figure 5.2, red arrow shows order of crystallization and blue arrow shows decreasing trend of stability). For example there is a general increase in chemical stability from olivine via-pyroxene, via-plagioclase, via-biotite via-muscovite to-quartz [11].

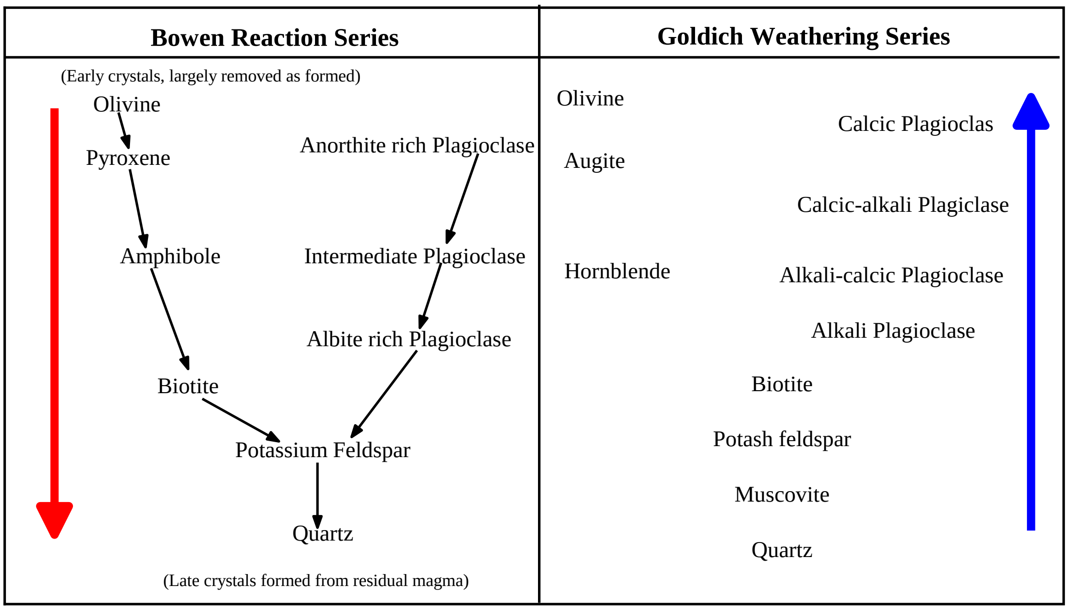

Fig 2: Weathering sequence in minerals versus Bowen's reaction series.

Weathering of primary minerals of basement rocks occurs at different rates and secondary minerals evolve from these in well-established sequences [34]. Primary alumino-silicate minerals found in crystalline rocks decomposes to more stable secondary minerals when come in contact with water, oxygen and carbon dioxide. The progressive weathering of plagioclase, K-feldspar and biotite (primary minerals) to secondary minerals is shown in Fig 3.

The secondary minerals appear, as primary mineral becomes more weathered and their order of appearance remains same irrespective of the nature of the climate [34]. Chlorite $[(Mg,Fe)_5Al_2Si_3O_{10}(OH)_8]$ in this sequence is a mesonorm [22] and sericite $[(K,Na)_2(Al,Fe,Mg)_3(Si,Al)_8O_{20}(OH)_4]$ is formed by the hydrothermal activity (or by alteration of feldspars) on feldspars [7]. Sericite and chlorite in the sequence are the result of retro-diagenesis of granites/granitic gneiss rather than the secondary weathering products [34]. Laterites are formed from the leaching of sedimentary, metamorphic, igneous and mineralized proto-ores which are predominantly iron and aluminium [35].

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 [18, 37] 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 [17] which facilitates weathering processes.

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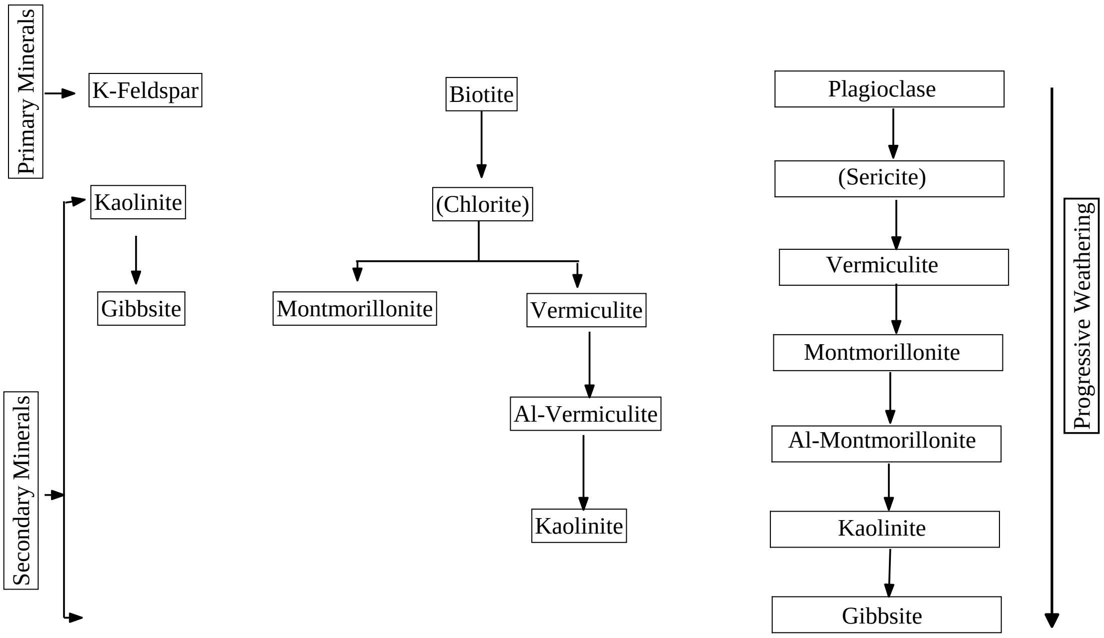

Fig 3: Progressive weathering of primary minerals to secondary minerals in crystalline rocks [34].

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 [1, 2, 8] 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, trace elements and REE of this laterite deposits were carried out so for. The purpose of this study is to investigate the chemical weathering of rocks, resulting into lateritization processes in one environmental setting. In this chapter it is mainly focused on mechanism and fractionation of major, trace and REE elements, particularly as a function of weathering intensity, and the factors affecting the mobilization and redistribution of selected elements during the processes lateritization at Swarnagadde plateau, Karnataka (Fig 4).

Typical weathering profile terminology. After Anand and Paine [2002]; Golightly [1981]

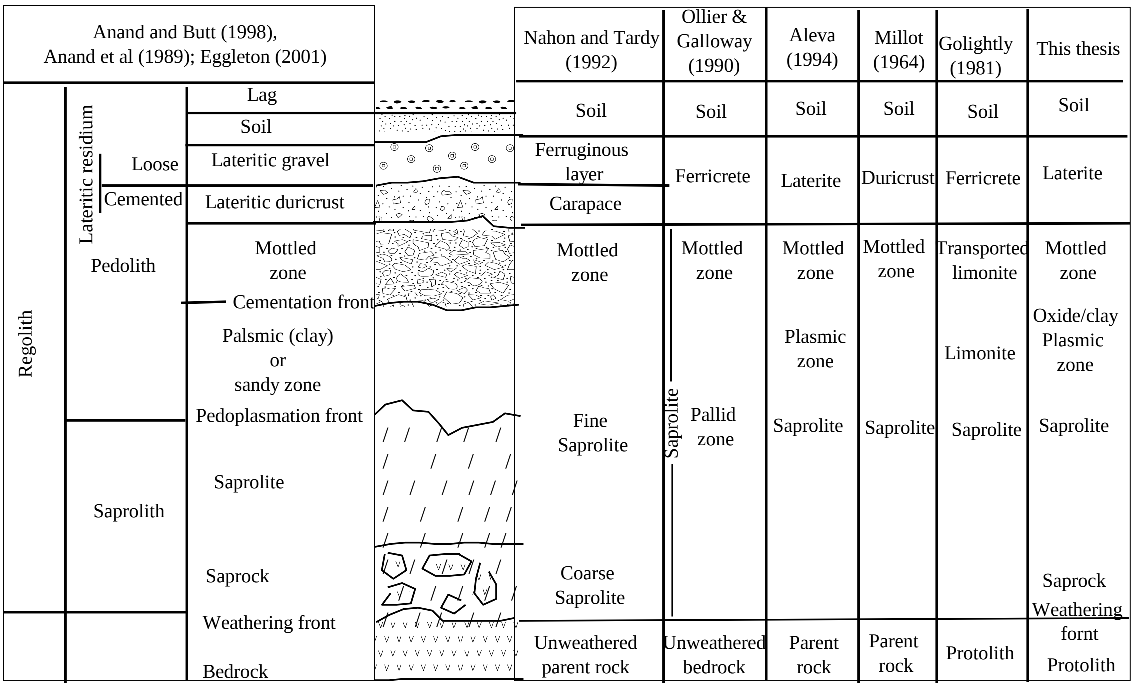

Fig 4: Typical laterite weathering profile terminology of the study area.

A.2: A Quantitative estimation of the degree of Lateritisation

The Schellmann system [29, 30, and 31] is a quantitative approach which compares the extent of chemical alteration of a weathering product to that of its protolith in order to define increasing degrees of Lateritisation. Significantly, the scheme recognises the importance of the nature of the protolith upon the composition of the weathering product; it also requires that the weathering products are entirely the result of *in situ* alteration processes. Using a SiO_2-Al_2O_3-Fe_2O_3 ternary diagram, four stages of alteration are recognised in the lateritisation process: (a) kaolinitisation, (b) weak lateritisation, (c) moderate lateritisation, and (d) strong lateritisation. The relative positions of these stages on the ternary diagram vary according to the chemical composition of the protolith. As a result, the Schellmann scheme proves useful for determining the degree of weathering for laterites. On the other hand, this scheme cannot be applied to separated phases since these involve allochthonous inputs of material into an alteration profile [6, 32]. However, where applied in combination with careful geomorphological and geological classification does offer significant insight into the alteration progression in a weathering profile [32, 38]. In view of that, Babechuk et al, [3] promoted use of SiO_2/ (Al_2O_3+Fe_2O_3) ratio and suggested that it should be referred to as the 'index of lateritisation' (IOL) or the 'index of bauxitisation' (IOB). To be consistent with the chemical classification of laterite and the SAF plot, they define the IOL using mass (wt. %) ratio of SiO_2, $Fe_2O_{3\,(T)}$, and Al_2O_3, as shown in the following equation.

$$IOL= 100x\ [(Al_2O_3+Fe_2O_3)/\ (SiO_2+ Al_2O_3+Fe_2O_{3\,(T)})]$$

The limit of kaolinitisation on the tri-plot for the protolith of the Swarnagadde profile (i.e. granitic gneiss) is determined to occur at 54.30% SiO_2, and the appropriate fields of increasing degree of lateritization are given in Fig 5. Deep weathering profiles are thought to develop through the downward progression of a weathering front, and the associated expansion of the saprolitic, mottled and lateritic zones behind it.

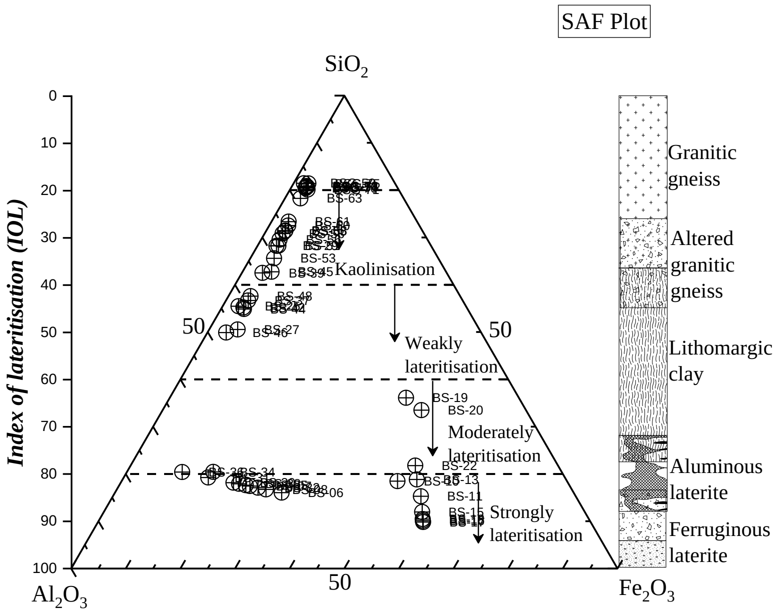

Fig 5: Mass SiO_2-Al_2O_3-Fe_2O_3 (SAF) ternary plots illustrating the different degrees of alteration in the weathering profile of Swarnagadde plateau. The index of lateritization (IOL) is integrated into SAF ternary diagram.

As a result, lateritic profiles of the Swarnagadde plateau have been formed in this fashion, then samples taken from increasingly higher levels within the weathering profiles should be more altered, and plot sequentially away from the origin (i.e. protolith composition), toward the strongly lateritised field on the tri-plot. The chemistry of the laterite profiles of the study area may be summarised in terms of the tri-plot (Fig 5) as follows:

The progression from fresh parent granitic gneiss to loss of Si and relative enrichment of Fe and Al involves through the altered granitic gneiss lying at progressively higher levels within a thick saprock zone; the latter displaying a relative depletion in mobile element concentrations. Some samples lies at the interface between the saprock and an overlying reddened zone; the latter marks the base of the saprolite proper zone. The saprolite itself has similarly undergone depletion in some mobile elements but, also displays both a slight Fe enrichment and silica depletion, thus placing it in the kaolinitized field of the tri-plot. At higher levels in the weathering profile (BS-27 & 46) are increasingly depleted mobile elements (Mg, Ca, Na, K, Rb and Sr), and progressive breakdown of primary silicates has resulted in significant loss of Si in to the weakly lateritised field of the tri-plot. Above the saprolite, the porosity of the profile increases markedly, and Fe-rich mottling consisting of highly ferruginous patches begins to dominate (i.e., mottled zone). Samples BS-19, 20, 22 and 13 represent a progression toward increasingly Fe-dominated secondary minerals through the effects of further mobilization of silica Al-loss from the neo-kaolinite. On the tri-plot these samples define a progressive trend from the weakly lateritised to the moderately lateritised field. The extreme either iron or aluminium enrichment of this material represents a further advancement of the processes of desilicification, removal of kaolinite, and volume collapse, associated with the evolution of the upper part of the lateritic weathering profile. In this lateritic weathering profile, samples BS-06, 07, 08, 36 and 11, 16, 20 represent a progressive trend from the moderately lateritised to strongly lateritisation field.

A.3: Chemical weathering: Estimation of weathering intensity-Chemical Index of Alteration (CIA)

Chemical changes that take place in the course of incipient to moderate levels of weathering processes, Ca, Na, Mg and K of the parent rocks are highly mobile and are easily leached out, ensuing 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 [22, 24, 26] will increase from the parent rock upward to the surface soil, suggesting the increasing of chemical weathering, accompanied through the conversion of more and more feldspar minerals to clay minerals, due to the fact it no longer only consists of potassium in its formation, but additionally 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 [12, 22, 23, 24], it has been used in numerous paleosol studies [33]. The degree of weathering profile samples have been calculated the use of the molecular proportion of the major element oxides to alkaline elements. Thereby, stoichiometric adjustments all through weathering are reflected in the index value.

$$\text{CIA} = [(Al_2O_3) / (Al_2O_3 + \text{Cao} + Na_2O + K_2O)] \times 100^{\text{(molar basis)}}$$

The laterite samples have an average CIA value of 97.56, ranging from 61.95 to 99.92, with the highest CIA values in ferruginous laterites and least in altered granitic gneisses of the study area. 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 of the studied area. Samples from the weathering profile of the study area are plotted using Al_2O_3-(CaO+Na_2O)-K_2O-(A-CN-K) ternary diagram (Fig 6), which demonstrates alteration trends in major element composition and minerals during the chemical weathering.

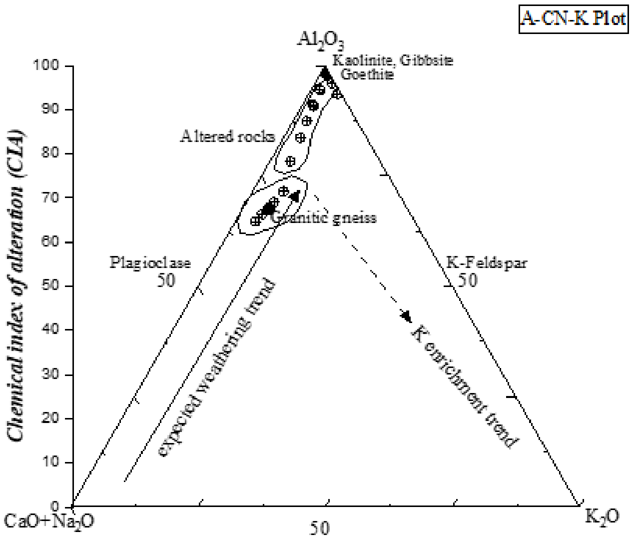

Fig 6 Molar Al_2O_3-CaO+ Na_2O-K_2O (A-CN-K) ternary plots illustrating different degrees of alteration experienced in the weathering profile of Swarnagadde plateau. The chemical index of alteration (CIA) is integrated into A-CN-K ternary plots.

The A-CN-K triangular diagram describes the outcome of chemical weathering of the upper crust where plagioclase and K-feldspar are dissolved, inflicting depletion of Ca, Na and K and enrichment of Al [22, 24]. Since 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 Al_2O_3 apex, kaolinite, halloysite and gibbsite are the predominant clay minerals. In the studied weathering profile, most regolith samples were tremendously weathered, and the plots cluster intently at Al_2O_3 apex, which displays the presence of phyllosilicate clay minerals as principal 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, proportion of clay minerals and the ratios of quartz to feldspar and K-feldspar to plagioclase increases, and the mineral components of weathering profiles are determined to a large extent with the intensity of weathering.

A.4: The mafic index of alteration (MIA)

The mafic index of alteration (MIA) is proposed by Babechuk et al [3] as a chemical weathering index that extends the equation of the CIA to include the mafic elements Mg and Fe. Many of the mafic minerals are susceptible to chemical weathering, resulting in the loss of Mg from weathering profiles. The loss of Mg can be monitored independently using the Mg index (MgI; Maynard, [19]. By contrast to Mg, the fate of Fe during the weathering of most mafic minerals is redox dependent. When the alteration environment is oxidizing and Fe is retained, total Fe is considered an immobile element along with Al (Al_2O_3) and the MIA calculation is:

$$\mathrm{MIA}_{(O)} = 100 \times [(Al_2O_3+Fe_2O_{3\,(T)}) / (Al_2O_3+Fe_2O_{3\,(T)} + MgO+CaO+Na_2O+K_2O)] \qquad (1)$$

When the alteration environment is reducing and Fe is leached along with Mg, total Fe is considered as mobile element along with Mg, Ca, Na, and K and the MIA calculation is:

$$\mathrm{MIA}_{(R)} = 100 \times [(Al_2O_3) / (Al_2O_3+Fe_2O_{3\,(T)} + MgO+CaO+Na_2O+K_2O)] \qquad (2)$$

In both arrangements of the MIA [$\mathrm{MIA}_{(O)}$ or $\mathrm{MIA}_{(R)}$], increasing index values represent progressively more altered rock, as is the case with the CIA. A value of 100 indicates complete removal of the mobile elements. As with the CIA, the MIA uses the molar ratios of the major element oxides by converting the wt% concentrations into moles. The molar CaO is corrected for the presence of carbonate and apatite as for the CIA (Fedo et al., 1995) to consider only the silicate-bound Ca (CaO*).

In addition to the index value, the proportional changes of the elements in the MIA can be studied graphically with ternary plots in the Al-Fe-Mg-Ca-Na-K system e.g., [23, 24] whereby both versions of the MIA are arranged into the plots in the same manner as the CIA with the A-CN-K diagram (Fig 7).

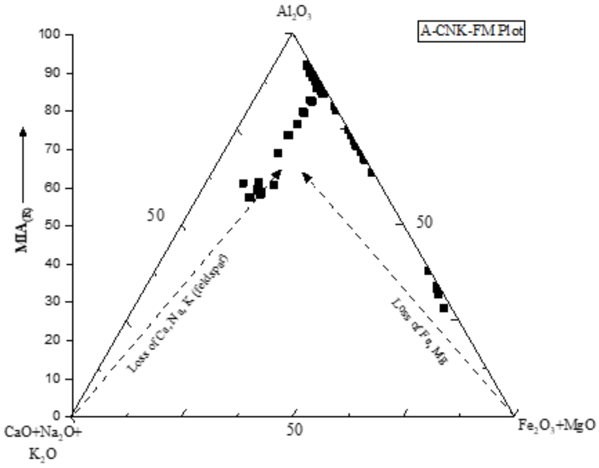

Fig 7: A-CNK-FM molar ternary plots proposed by [23] exposes the contribution of mafic and felsic mineral components to rock weathering of the study area. The integration of new mafic index of alteration (MIA) into AFMNCK space is illustrated after [3].

A.5: The A-CNK-FM diagram

The A-CNK-FM ternary diagram was proposed by Nesbitt and Young [23] reflecting the mafic mineral component in rock weathering. In this plot (Fig 7), the feldspar (felsic) weathering line is supposed to follow a direction approximately

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away from the CNK apex through the position of the unweathered sample. The exact magnitude and direction is largely influenced by the rate of feldspar weathering and the type of secondary weathering product. The loss of Fe and Mg from the mafic minerals should result in a weathering line that emanates away from the FM apex through the unweathered sample. During oxidative weathering, however, Fe is not typically lost from the system. This complicates the mafic weathering trends and contributes to the difficulty in predicting the overall rock weathering line [23, 24]. A net weathering line emanating away from the CNK apex suggests a greater relative mobility and more extensive leaching of Ca, Na, and K compared to Mg. This may be misleading, however, since Mg is known to exhibits a similar bulk weathering behaviour to Ca and Na [24].

Thus the behaviour of Fe and Mg is not accurately represented in the plot due to their contrasting behaviour in most (oxidative) weathering environments. It is not until Ca, Na, and K are depleted and the stages of advanced weathering are reached that change in the relative proportion of Mg, Fe and Al are recorded on the A-CNK-FM plot [23]. This is recognized by the lateritised Swarnagadde samples in Fig 7, which fall on the A-FM axis and are a function of the relative proportion of aluminous (e.g., gibbsite, kaolinite) and ferruginous (e.g., hematite, goethite) pedogenetic products.

According to Babechuk et al [3] it is suggest that the A-CNK-FM diagram is most applicable to weathering environments in which Fe^{2+} is mobile and behaves like Mg during chemical weathering (i.e., in reduced geochemical environments, such as recorded in Archaean and early Proterozoic weathering profiles). In these environments, loss of Mg and Fe is summative and results in a mafic mineral weathering line away from FM apex. Ultimately, this would result in a net weathering line that is directed away from the CNK-FM axis towards the A apex.

A.6: The A-L-F diagram

Nevertheless, the other details to the competing Fe and Mg lines of the A-CNK-FM diagram is the A-L-F diagram of [24], where Mg is moved to the same apex as Ca, Na, and K (Fig 8). These four elements comprise the total labile (L) cation content. The upper apex is Al and the remaining axis becomes total Fe. In this plot, the net rock weathering line is predicted to emanate away from the L apex through the position of the unweathered sample as Ca, Na, K, and Mg are lost. The magnitude of this line represents the degree of element loss during weathering. Complete loss of these elements would result in the trend reaching the A-F axis. Accordingly, the MIA $_{(O)}$ value in the A-L-F plot is equivalent to the tie line joining the L-A and L-F axes, with values increasing towards the A-F tie axis (MIA value of 100).

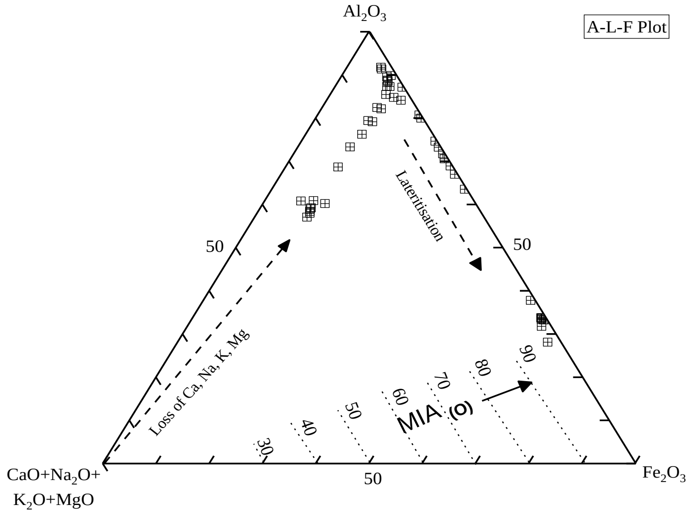

Fig 8: A-CNKM-F (A-L-F) molar ternary plots proposed by [24] exposes the contribution of mafic and felsic mineral components to rock weathering of the study area. The incorporation of new mafic index of alteration (MIA) into AFMNCK space is illustrated after [3].

Though, $MIA_{(O)}$ values attain a maximum at the A-F axis, one advantage of the A-L-F plot is that advanced weathering trends can be graphically visualised by trends moving towards the Fe apex (lateritisation) or the Al apex (bauxitisation). The proportion of the aluminous and ferruginous minerals in the advanced weathering residue can be extracted from the plot based on the sample position trend along the A-F axis [21]. As a result, the Swarnagadde plateau samples plot along the A-F axis moving towards the A-F apex, demonstrating the Al and Fe enrichment in the profile (Fig 8). As a result, the plot is also useful for assessing the net behaviour of Fe (i.e., enrichment or loss) during weathering in modern and ancient weathering profiles, similar to the A-M-F plot [39].

V. CONCLUSIONS

Many of the geochemical characteristics of lateritic weathering profiles are related to the development of the profile by the downward progression of the weathering front and the development of the associated zones behind it, but processes such as the establishment of a stable water table may serve to modify this idealised lateritic profile (Fig 1). The behaviour of major and minor elements during the development of laterites have been suitably summarised for Australian examples by Butt et al. (2000), and relates the leaching and retention of a range of elements to mineral transformations in the principal horizons of the weathering profile.

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