Highly mature sediments in the tropical monsoonal environment of southwestern India: an appraisal based on weathering indices

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Abstract

Purpose – This paper aims to examine the geochemical change experienced by laterites in Kerala, India, subjected to tropical monsoonal climate. These sediments are underlain by hard rock. The source rock characteristics have a major stake on the ultimate composition of sediments, as also the climatic conditions which an area experience.

Design/methodology/approach – Core samples have been obtained from several locations in a lateritic plateau. The upper portions of the borehole cores are composed of the lateritic hard cap, followed by lateritic soils. The soil samples were subjected to sediment texture analysis and XRF analysis (Bruker S4 Pioneer Sequential Wavelength-Dispersive XRF) for the determination of major elements ((in oxide form).

Findings – Major element geochemistry has revealed the following order of relative proportions of elements (in oxide form) $SiO_2 > Al_2O_3 > Fe_2O_3 > TiO_2 >> Na_2O > P_2O_5 > CaO > K_2O > MgO > MnO$. Even though the concentrations of SiO_2, Al_2O_3 and Fe_2O_3 contribute 90% of major element chemistry, there is no significant correlation found for these elements within themselves or with others.

Research limitations/implications – Microscale movement of elements could not be characterised in this study. This requires access to an electron probe micro analyzer.

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Practical implications – The practical implication of tropical weathering is that enhanced chemical leaching leads to movement of most elements out of the system, except for Al, leading to the possible formation of bauxite, or aluminous laterite.

Social implications – The weathered products in this study provide livelihood sustenance for many of the local households, through manual production of laterite bricks, which are used in construction.

Originality/value – The indices of the intensity of chemical alteration/weathering like chemical index of alteration (CIA), chemical index of weathering (CIW) and weathering index of parker (WIP) reveal that the sediments indicate intense weathering of the source area prior to being deposited in the present location. This indicates enhanced monsoonal activity in the provenance areas, than that obtained today.

Keywords Kerala, Chemical index of alteration (CIA), Chemical index of weathering (CIW), Laterite, Weathering index, Weathering index of parker (WIP)

Paper type Research paper

1. Introduction

The chemical breakdown of unstable minerals and the formation of new ones is the key geochemical process in sedimentary environments. Climate and tectonism play an important role in the relative rate of weathering of minerals and/or rocks (McLennan and Taylor, 1991; Selvaraj and Chen, 2006; Meschede and Warr, 2019) . The rate of production of new geochemical constituents in a warm and humid climate is much higher than that of cold and dry climates (Liu *et al.*, 2020; Lasaga *et al.*, 1994). One of the most efficient tools for unravelling the palaeoclimatic conditions that prevailed during the depositional processes is geochemical studies of silicate and non-silicate mineral phases in sediments (Clift *et al.*, 2002; Li *et al.*, 2004; Mishra *et al.*, 2019; Yang *et al.*, 2003, 2004, 2007). Although several geochemical tools have been widely used in many parts of the world, not enough studies have been reported from the Indian subcontinent to decode the past climatic conditions in the sedimentary archives (Mishra *et al.*, 2019; Sarin *et al.*, 1979; Das and Krishnaswami, 2007; Pattan *et al.*, 2008; Veena *et al.*, 2013; Tripathy *et al.*, 2014; Kumaran *et al.*, 2018). Here an attempt has been made to address a few aspects of sediment geochemistry of borehole cores retrieved from the northern part of Kerala of Peninsular India to decode partially the palaeoclimatic records.

The clastic sediments are the outcome of a complex geochemical process that took place during chemical weathering of the source area, abrasion and hydrodynamic sorting and mixing during transportation and deposition (Johnsson, 1993; von Eynatten, 2004; Roy *et al.*, 2006). The composition of the clastic sediments is modified further by diagenesis and sediment recycling, and this renders climatic reconstruction based on sediment composition a difficult process. The net product will have a new composition, quite different from the composition of the source rocks. One of the greatest challenges in the study of sediments and sedimentary environments is to figure out the initial sediment composition and also the proportional contributions of individual processes like climate change effects, intensity of chemical weathering, diagenetic contributions or combination of all these processes in the formation of the end products which is subjected to the study (Ghosh and Guchhait, 2020).

However, the source rock characteristics have a major stake on the ultimate composition of sediments. Therefore, model analyses of sediments are often used to infer the geo-environmental setting of the provenance of detrital sediments (Dickinson and Suczek, 1979; Dickinson, 1985; Nesbitt and Young, 1996; Cullers, 2000).

2. Aims and objectives

The present study aims to understand the geochemical changes experienced by weathered rocks in a location in Kerala, subject to tropical monsoonal climate. Such an understanding will help in constraining the intensity of past rainfall, as well as to know whether natural weathering has led to the formation of sub-aerial economic deposits like bauxite and/or aluminous or ferruginous laterite. Thus the problem being examined in the study is about the formation of extensive deposits of weathered material, whether it was due to enhanced rainfall in the past, and the economic aspects of the deposits.

3. Materials and methods

The area of investigation is flanked to the east by the hills of the Western Ghats and to the west by the Arabian Sea (Figure 1). The annual average rainfall is 3,438 mm, and more than 80% of it occurs during the period of southwest monsoon (June to September). The average mean temperature ranges from 19.7 to 36.9°C. These are conditions suitable for chemical weathering and leaching of elements. The methodology consists of fieldwork, sampling and chemical analyses and interpretation of the data.

Systematic fieldwork was carried out in the study area to collect relevant primary and secondary data on various landform features, geological setting of the area and locating the borehole sites (Figures 2, to 4). Samples of three stratigraphic columns, BH1, BH2 and BH3, spatially separated from each other, were collected from the study area in Kerala during drilling

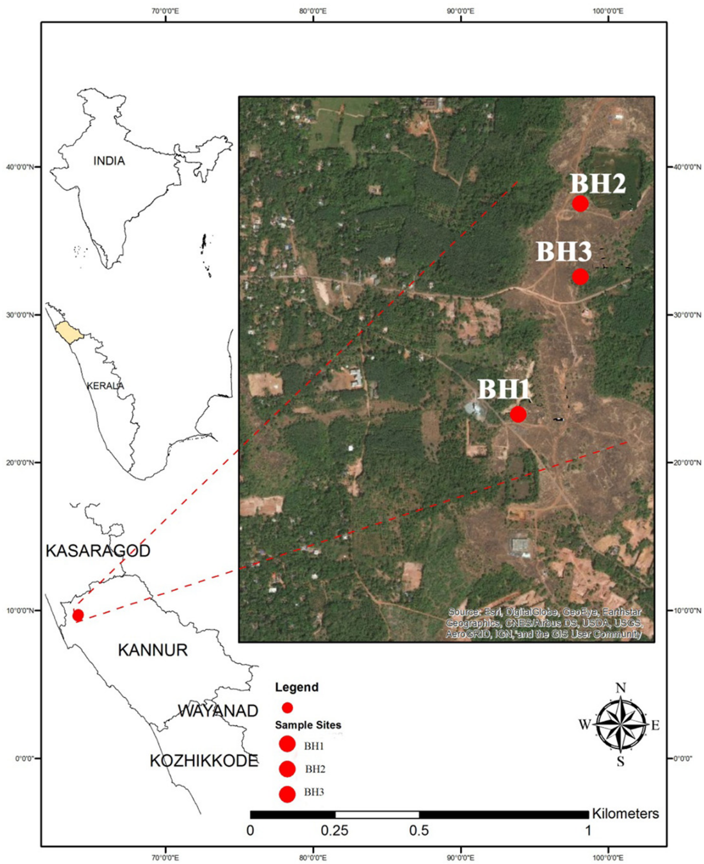


Figure 1.
Location of the boreholes in the study area in Kerala, India

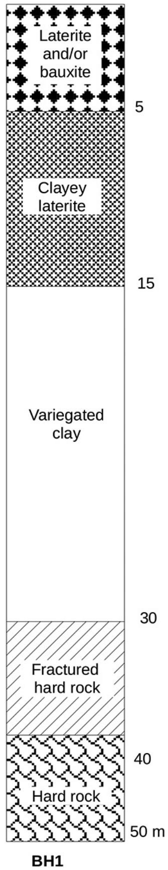


Figure 2.
Litholog of bore hole 1 (BH1)

for foundations of infrastructure projects, and these are located at an elevation of 75 m above mean sea level (MSL). Several samples of varying lithology (pedogenic horizons and parent/bedrocks) were obtained from these cores. The sampling locations are situated in an area with low interference of human activities. All the three sites are located in a plateau-like terrain with hard cap of laterite on the surface. The general geological formation of the area is mainly laterite of Quaternary age at the top, followed by variegated clay with yellow, red and pink patches and yellowish clay of Tertiary age overlying the Archean basement of hornblende gneiss. Each core contains laterite/bauxite, clay, sand, peat and iron formation. The profiles are between 40 to 50 m in thickness.

After documenting the lithological characteristics, the borehole cores were sectioned as per lithology and the sub-samples were packed in neatly labelled polyethylene bags for further analysis. Sub-samples from selected depths were subjected to textural analysis (Lewis, 1984). The ternary diagram (Picard, 1971) was used for the classification of sediments. A few representative samples from selected borehole cores were powdered to 200 ASTM mesh size and subjected to XRF analysis (Bruker S4 Pioneer Sequential Wavelength-Dispersive XRF) for the determination of major elements (in oxide form). The elements analysed include Si, Al, Ti, Mn, Fe, Ca, Mg, Na, K and P. The Bruker XRF is equipped with a goniometer and Spectraplus software for the

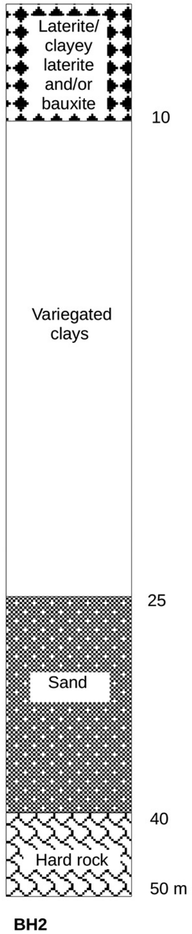


Figure 3.
Litholog of bore hole 2 (BH2)

qualitative and quantitative determination of the elements. Analyses were performed on pressed pellets for trace elements and fusion glass disks for major elements. Fused glass disk was prepared using a Claisse Fluxy fusion bead instrument. Pressed pellets were prepared using an Insmart 40-ton press. All the analyses were carried out in the National Centre for Earth Sciences Studies, Trivandrum, India.

4. Results and discussion

4.1 Lithlogical characteristics

The borehole cores are located in a lateritic plateau. The upper portions of the regolith are composed of the lateritic hard cap, followed by lateritic soils. From the ternary diagram of Picard (1971) (Figure 5), the sediment types are sandy loam, sandy clay loam, sandy clay, fine loamy sand, fine sand, silty clay loam, silt loam, sandy clay loam, silty clay, loam and clay. The whole

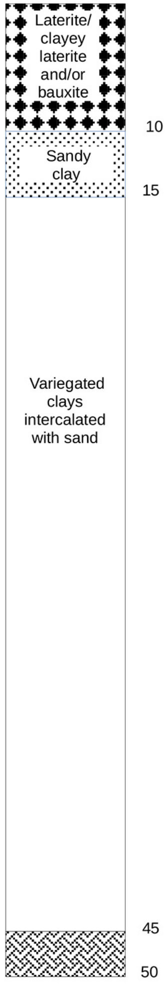


Figure 4.
Litholog of bore hole 3 (BH3)

borehole core rests over hornblende gneiss. The following paragraphs give a brief account of the lithological characteristics of the borehole cores.

Based on the lithological characteristics, BH1 is divided into three horizons. The lateritic hard cap, red to pink variegated clay and sandy clay-rich horizon and sand dominates the horizons. The upper lateritic hard cap and lateritic soils extends up to a depth of 4.6 m from surface and lies on the red to pink variegated clay, and sandy clay-rich horizon. The ranges of sand, silt and clay contents are 2.86–61.80% (av. 37.86%), 0.99–24.90% (av. 14.41%) and 14.90–79.69% (av. 47.72%) respectively. The sediment types present in this horizon are clays, sandy clays, sandy clay loam and sandy loam. This horizon extends to a depth of up to 25.5 m depth from 8.5 m. This horizon lies above the sand dominated horizon. This sand dominated horizon has a depth of up to 42 m from 25.5 m. A peat formation is present in this zone, which has a width of just 0.3 m. The peat formation contains sand. The sediment types present in this

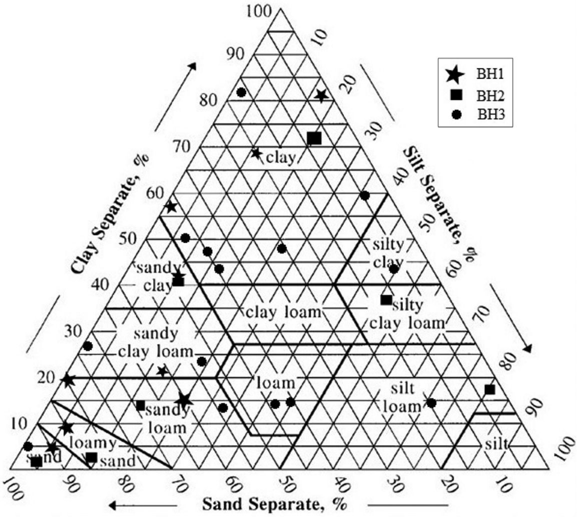


Figure 5.
Sediment types (after Picard, 1971) of the borehole samples

horizon are sandy loam, sandy clay, fine loamy sand and fine sand, in between these sediments weathered rock fragments with clay are also present. The ranges of sand, silt and clay contents in this horizon are 49.57– 90.62% (av. 76.75%), 0.24–6.08% (av. 4.84%) and 5.26–41.48% (av. 18.40%) respectively.

The BH2 borehole core also has three horizons, the upper lateritic hard cap and lateritic soil extends up to 4.2 m, which lies on the red to pink variegated loam and clay-rich horizon. The ranges of sand, silt and clay contents are 9.31–70.75% (av. 35.06%), 9.68–49.97% (av. 19.70%) and 13.23–70.97% (av. 23.84%) respectively. The sediment types present in this horizon are silty clay loam, sandy loam, sandy clay and clay. This zone extends up to 24 m from 10 m and lies on the sand dominated horizon. The ranges of sand, silt and clay contents are 3.86–96.77% (av. 61.92%), 3.15–79.51% (av. 32.00%) and 0.06–16.61% (av. 42.34%) respectively. The sediment types present in this horizon are sand, silt loam, fine loamy sand. Peat deposition is seen in between sand and silt loam at a depth of 25–26 m. The last unit in all the three cores is hornblende biotite gneiss.

The BH3 borehole core has four horizons. The first horizon, the lateritic hard cap and the laterite with soils extends to a depth of 4.5 m from the surface. This lies on the second horizon, which consists of red to pink variegated clays and loams. This horizon extends up to 15.2 m. The ranges of sand, silt and clay contents are 8.20–53.90% (av. 27.88%), 23.26–58.94% (av.34.97%) and 13.62–58.94% (av.42.34%) respectively. The sediment types present in this horizon are sandy clay loam, silty clay, clay, loam. The third horizon consists of greyish clays and clay loams and peat formation. This horizon has a depth of 23 m from 15.2 m. The ranges of sand, silt and clay contents are 17.51–73.46% (av. 43.99%), 0.29–12.14% (av. 4.52%) and 2.24–46.86% (av.51.47%) respectively. At a depth of 18.5 to 19.4 m, peat formation is observed in this horizon. The sediment types present in this horizon are sandy clay loam and clays. This horizon lies on a fine-textured sand deposit. This formation has a depth of 30 m from 23 m. The last horizon of this borehole core is a mix of white and grey coloured clays and loams. The ranges of sand, silt and clay contents are 15.68–55.08% (av. 39.36%), 6.62–70.45% (av. 33.93%) and 12.81–49.70% (av. 26.69%) respectively. This horizon extends up to a depth of 49.5 m from 30 m. The sediment types present in this zone are clay, loam, sandy loam and silt loam.

4.2 Major elements

The results of the major element analysis for the sediments of borehole cores are compared with the results of the Singo granites (SINGO) (Nagudi *et al.*, 2003), Upper Crust (UC) and Post-Archaean Australian Shale (PAAS) (Taylor and McLennan, 1985) and North American Shale Composite (NASC) (Gromet *et al.*, 1984) and presented in Table 1. The downcore variation of major elements (expressed as oxide form) in the BH1 borehole [(Figure 6(a)] such as SiO_2 (51.54–86.48%, av. 64.18%), and shows moderately higher concentrations, whereas Al_2O_3 (6.04–37.23%, av. 19.86%), Fe_2O_3 (6.04–35.22.per cent, av. 16.99%) and TiO_2 (0.27–1.66%, av. 0.95%) exhibit a reverse trend. The other major elements such as CaO, Na_2O, MgO, MnO, P_2O_5 and K_2O, show very low concentration. BH1 [Figure 6(b)] and BH2 [Figure 6(c)] borehole cores also exhibit similar trends in major element chemistry.

In the BH1 profile, the clayey sand horizon of 33 m depth shows high SiO_2 concentration (86.48). A clayey sand horizon is also seen at 25.5 m depth, and the SiO_2 concentration of this horizon is 57.7%. The brownish lateritic clay horizon of depth 11 m shows a high concentration of Al2O3 (37.23%), and the peat horizon shows the least concentration for Al2O3 (6.04%). For

Depth (m)	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	Na_2O	K_2O	P_2O_5
BH1										
14.50	67.36	1.49	14.19	11.74	0.06	0.01	0.03	0.11	0.03	0.09
17.40	62.07	1.66	22.3	5.08	0	0	0.05	0.14	0.02	0.05
18.60	58.66	1.11	29.42	0.84	0	0	0.06	0.11	0.01	0.03
26.25	57.94	0.63	8.92	0.88	0.02	0	0.02	0.09	0.01	0.02
28.50	54.19	1.55	35.22	0.99	0.07	0	0.07	0.01	0	0.05
30.15	51.54	0.27	6.04	1.66	0.05	0.01	0.04	0.1	0.02	0.02
32.00	86.48	0.69	8.54	1.11	0.11	0.01	0.09	0.13	0.03	0.02
41.25	75.22	0.17	11.26	4.85	0.83	0.05	0.39	0.55	0.58	0.03
BH2										
3.60	12.55	2.54	32.36	35.88	0.01	0.01	0.02	0	0	0.33
21.00	50.17	1.6	26.14	2.43	0.04	0.01	0.09	0.09	0.03	0.04
24.50	93.29	1.54	2.73	1.29	0.02	0.01	0.03	0.07	0.01	0.03
27.50	47.86	0.99	37.19	1.73	0.17	0.01	0.1	0.02	0.7	0.04
36.75	64.13	0.45	18.12	4.42	0.17	0.07	1.57	6.04	2	0.26
BH3										
5.63	18.79	2.3	38.84	22.06	0	0	0.01	0.07	0.05	0.18
10.70	60.4	1.82	21.21	1	0.03	0.01	0.03	0.09	0.02	0.03
11.85	40.48	1.02	5.3	47.52	0.03	0	0.01	0.06	0.01	0.03
15.10	34.69	0.77	20.64	8.28	0.05	0.01	0.05	0.09	0.03	0.02
18.95	35.03	1.05	29.45	4.46	0.02	0	0.13	0	0	0.03
22.75	78.73	1.56	14.75	0.74	0.05	0	0.03	0.11	0.01	0.04
26.50	94.48	0.74	2.85	0.66	0.05	0.01	0.03	0.09	0.02	0.02
30.05	50.58	1.01	25.47	12.31	0.04	0.01	0.06	0.1	0.02	0.07
33.30	51.03	2.62	35.42	2.08	0.04	0	0.03	0.02	0.05	0.07
44.15	31.85	1.01	15.41	26.54	4.29	0.43	0.46	0.38	0.67	0.04
47.70	36.92	0.91	14.43	27.8	1.52	0.52	1.36	0.8	0.49	0.05
49.20	29.35	0.69	12.38	32.77	1.51	0.57	1.08	1.45	0.34	0.05
SINGO	*72.65*	*0.42*	*13.33*	*2.60*	*0.60*	*0.08*	*1.09*	*3.54*	*4.87*	*0.13*
PAAS	*62.80*	*1.00*	*18.90*	*7.22*	*2.20*	*0.11*	*1.30*	*1.20*	*3.70*	*0.16*
NASC	*64.80*	*0.70*	*16.90*	*5.65*	*2.86*	*0.06*	*3.63*	*1.14*	*3.97*	*0.13*
UC	*66.00*	*0.50*	*15.20*	*5.00*	*2.20*	*0.08*	*4.20*	*3.90*	*3.40*	-

Note: Values are given in percentage

Table 1. Concentration of major elements (expressed as oxides) in the borehole cores Values are given in percentage

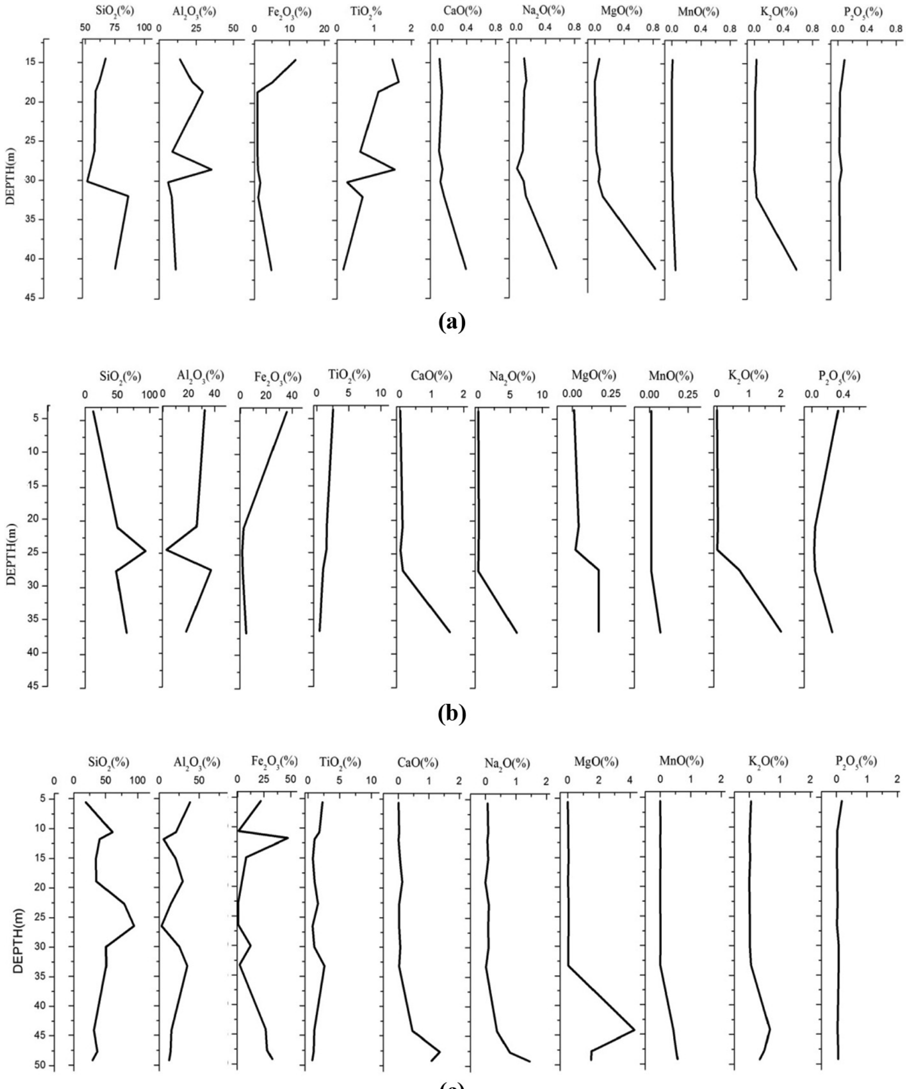


Figure 6.
Down core variation of major elements in the BH 1(a), BH2 (b) and BH 3 (c) borehole sediments retrieved from the study area

Fe_2O_3 brownish sandy clay horizon has the highest (11.74%) concentration and the pinkish variegated clay of 18 m depth shows the least concentration (0.84). The oxides of Magnesium, Sodium (alkali metals), Calcium, and Potassium, (alkaline earth metals) show very minute concentrations in this borehole. The order of relative proportions of the major elements (in oxide form) of all the three borehole core are $SiO_2 > Al_2O_3 > Fe_2O_3 > TiO_2 > Na_2O > P_2O_5 > CaO > K2O > MgO > MnO$. Even though the concentrations of SiO_2, Al_2O_3 and Fe_2O_3 contribute 90% of major element chemistry, there is no significant correlation found for these elements within them or with others.

4.3 Discussion

The evolutionary phases of sediment composition and provenance are usually understood by many statistical relations and proxy analysis like Chemical Index of Alteration (CIA), Weathering Index of Parker (WIP), Chemical Index of Weathering and diagrams like the relationship between CIA and WIP, A-CN-K, A-CNK-FM, etc (Biondino *et al.*, 2020; Nesbitt and Young, 1984; Cox *et al.*, 1995; Descourvieres *et al.*, 2011). To understand the weathering trends, two types of ternary diagrams are used here 1) A-CN-K [Al_2O_3-(CaO+Na_2O)-K2O] and 2) A-CNK-FM [Al_2O_3-(CaO+Na_2O+K2O)-Fe_2O_3+MgO] diagrams (Nesbitt *et al.*, 1996). In both the diagrams, the samples fall close to the Al_2O_3 end, signifying intense weathering in the source area before being deposited in the present location (Figure 7).

The intensity of chemical alteration/weathering such as CIA (Chemical Index of Alteration) (Nesbitt and Young, 1984); CIW (Chemical Index of Weathering) (Nyakairu and Koeberl, 2001); and WIP (Weathering Index of Parker) (Parker, 1970) were worked out using the equations (1)–(3) (given below) (Table 2).

The data and plots reveal that the sediments in the BH1 borehole core are much more altered than the sediments of BH2 and BH3.

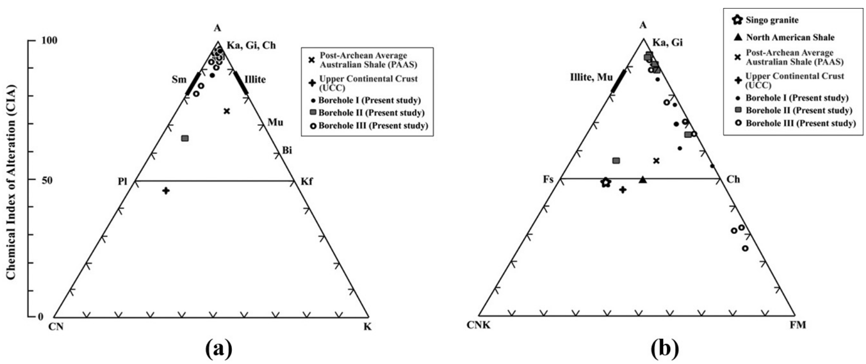
$$\mathrm{CIA} = \left[\mathrm{Al2O3}/(\mathrm{Al2O3} + \mathrm{Na_2O} + \mathrm{K2O} + \mathrm{CaO})\right] \mathrm{x}\,100 \;\ldots\ldots\ldots\ldots \quad (1)$$

$$\mathrm{CIW} = \left[\mathrm{Al2O3}/(\mathrm{Al2O3} + \mathrm{CaO} + \mathrm{Na_2O})\right] \mathrm{x}\,100 \;\ldots\ldots\ldots\ldots \quad (2)$$

$$\mathrm{WIP} = [\mathrm{Na}^*/0.35 + \mathrm{Mg}^*/0.9 + \mathrm{K}^*/0.25 + \mathrm{Ca}^*/0.7]\,\mathrm{x}\,100 \;\ldots\ldots\ldots\ldots \quad (3)$$

[where the cations* represent atomic percentage of an element divided by the atomic weight.]

Nesbitt and Young (1984) reported that CIA values of nearly 100 are obtained for kaolinite and chlorite and 70–75 for average shales. Taylor and McLennan (1985) reported CIA values between 85 and 100 for residual clays. Condie (1993) revealed that most PAAS



Notes: Ka: Kaolinite, Gi: Gibbsite, Mu: Muscovite, Fs: Feldspar, Ch: Charnockite, Ka: Kaolinite, Gi: Gibbsite, Ch: Chlorite, Il: Illite, Kf: Potash feldspar, Pl: Plagioclase, Sm: Smectite (after Nesbitt and Young, 1982, 1984; Nesbitt and Young, 1996; Dickinson, 1985; Descourvieres *et al.*, 2011)

Figure 7.
(a) (Al_2O_3)–A (CaO+Na_2O)–CN (K_2O)-K diagram and (b) (Al_2O_3)–A (CaO+Na_2O+K_2O)–CNK (Fe_2O_3+MgO)-FM diagram of the borehole sediments

Depth (m)	Sediment type	WIP	CIA	CIW
BH1				
14.5	Sandy loam	1.01	98.146	98.36
17.4	Sandy clay loam	1.29	98.48	98.58
18.6	Clay	1.01	98.98	99.02
26.25	Sandy loam	0.83	97.85	97.97
28.5	Sandy clay	0.095	99.59	99.59
30.15	Sand	0.92	95.89	96.22
32	Loamy fine sand	1.20	95.4	95.76
41.25	Fine sand	5.15	83.39	87.46
BH2				
3.6	Sandy clay	0.00078	99.88	99.88
21	Sandy clay	0.83	98.70	98.82
24.5	Fine sand	0.64	93.79	94.14
27.5	Silt loam	0.25	97.45	99.42
36.75	Loamy fine Sand	55.90	54.78	58.62
BH3				
5.625	Sandy clay loam	0.64	99.51	99.65
10.7	Clay	0.83	98.95	99.05
11.85	Loam	0.55	97.64	97.84
15.1	Loam	0.83	98.70	98.85
18.95	Loam	0.0038	99.20	99.20
22.75	Sand	1.01	98.35	98.42
26.5	Fine sand	0.83	92.70	93.36
30.05	Clay	0.92	98.85	98.93
33.3	Clay	0.19	99.60	99.75
44.15	Silty clay	3.69	87.57	91.33
47.7	Loam	7.49	76.96	79.20
49.2	Sandy loam	13.46	72.41	74.00

Table 2. Sediment type, weathering index of parker (WIP), chemical index of alteration (CIA) and chemical index of weathering (CIW) of the borehole sediments

values show moderate loss of Ca and Na from source weathering with CIW values of 80 to 95. On the contrary, PAAS shows greater loss of all the three elements, with CIW values between 90 and 98. Regarding WIP, the values between 80 and 100 are for fresh rock and values between 0 and 70 generally show high intensity of weathering. The data demonstrate that WIP appears to be sensitive to small changes in the concentration of the major cations. The WIP values vary from 0.09 to 5.15 for borehole BH1, 0.0007 to 55.91 for borehole BH2 and 0.003 to 13.46 for borehole BH3. This clearly indicates that the samples of BH1 are more weathered/altered than that of BH2 and BH3.

The interrelationship between WIP and CIA is depicted in Figure 8. CIA and WIP values for the borehole core sediments of BH1 fall in the field of WIP 0 and 5. The CIA 85 and 100 indicate the maturity of the sediments. The plots of the borehole BH2 spread in the field 0 and 55 for WIP and 55 and 100 for CIA. For BH3 core, the values are 0 and 15 for WIP and 72 and 100 for CIA. These values reiterate that the sediments of the borehole cores of BH1 are altered more than that of BH2 and BH3.

5. Conclusion

The geochemistry of the sediments reveal that the three major elements in oxide forms, such as SiO_2, Al_2O_3 and Fe_2O_3 together constitute more than 90% of the total geochemical constituents. The other elements are present only in substantially lower percentages. Geochemical discrimination procedures such as CIA, WIP and CIW weathering indices and, A-CN-K and A-

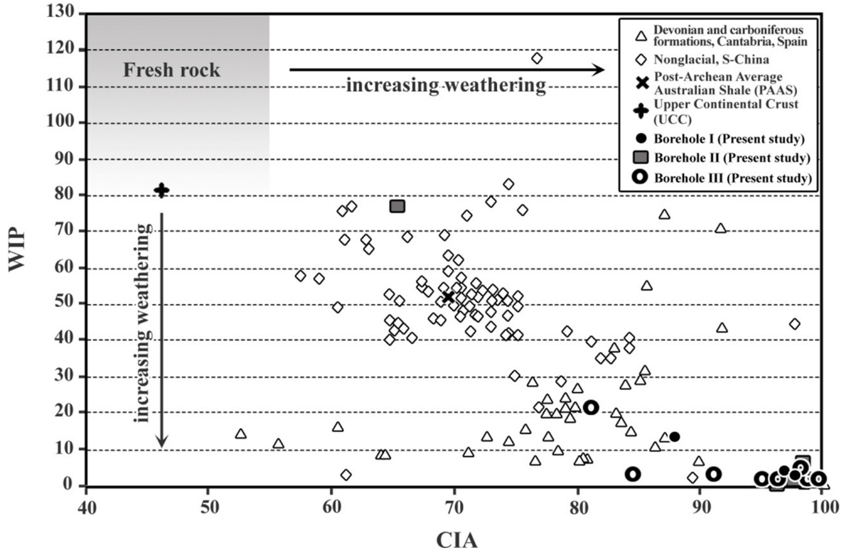


Figure 8.
Interrelationship between two weathering proxies – weathering index of parker (WIP) and chemical index of alteration (CIA) worked out for the borehole sediments

CNK-FM ternary diagrams which were used to draw information on the intensity of weathering/alteration of the borehole core sediments of the study area demonstrate that the values plots close to the Al_2O_3 end, indicating intense weathering of the source area prior to being deposited in the present site. In all the three cores, the ternary plots are seen clustered towards the Al_2O_3 end. All these computational results indicate the differences in the depositional processes, as well as the degree of maturity of sediments in the three cores which has undergone tropical weathering. The sediments in the area have thus undergone multiple cycles of weathering and are the products of intense tropical monsoonal weathering from the past. They could undergo further weathering over geological time, and potentially, these sediments could all turn into bauxites, given that they remain unexploited and *in situ*. In conclusion, it is these sediment profiles which give palaeoclimatologists and soil scientists adequate information to model climate change and its impacts on soil formation and resource enrichment.

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