www.gondwanags.org.in

Original Article

ISSN : 2455-1953

JGSR

Journal of Geosciences Research

Vol. 7, No.2, July, 2022, pp. 159-165

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Palaeoclimatic Imprints as Revealed from the Studies of Intrabasaltic Bole Beds of the Deccan Traps, Maharashtra, India

M.M. Shaikh[1]*, M.R.G. Sayyed[2] and D.C. Meshram[1]

[1] Geology Department, Savitribai Phule Pune University, Pune -411007(MS), India
[2] Geology Department, Poona College, Camp, Pune -411001(MS), India
*(*Corresponding author, E-mail: mohsin511984@yahoo.co.in)*

Abstract

Geochemical characteristics of four Deccan intrabasaltic bole bed profiles occurring around Yelapur area of Sangli District (Maharashtra, India) were used in deducing the palaeoclimatic conditions prevailed during their formation. Higher Chemical Index of Weathering (CIW) values for all the four red boles indicate considerable chemical weathering and much leaching of the bases while the values of Parker's Weathering Index (PWI) show slight variations. Almost similar Mean Annual Temperature (MAT) values for all the red boles suggest their formation under moderate temperatures while Mean Annual Precipitation (MAP) values indicate slight variations in rainfall. Although quite variable the Iron Species Ratio values indicate oxidizing conditions while Product Index values suggest somewhat acidic conditions during the formation of red boles. Hydrolysis values in red boles indicate mostly humid conditions while values of Salinization are well below unity indicating that the red boles were formed under fairly leached conditions. A–CN–K plots for all four red bole profiles point their weathering trends towards smectite formation while SiO_2– Al_2O_3–Fe_2O_3 plots indicate kaolinization stage for bole beds suggesting their incipient weathering without lateritization. Thus, these four red bole profiles were formed under somewhat humid, fairly leached, relatively well-drained and rather acidic conditions under variable rainfall.

Keywords: Intrabasaltic Bole Beds, Palaeoweathering, Geochemistry, Deccan Traps, India.

Introduction

Large igneous provinces (LIPs) covering millions of square kilometers of the earth surface (Coffin and Eldholm, 1994) have been widely distributed during the earth history both spatially and temporally amongst which some are sub-marine while others are terrestrial (Jerram and Widdowson, 2005). The Deccan volcanic province is the region encompassing a series of Maastrichtian to Paleocene (Danian) continental flood basalts estimated to comprise a volume of more than 1.3 million km^3 (Jay and Widdowson, 2008; Schoene *et al.*, 2015) which are projected to have extended about 1,500,000 km^2 (Krishnan, 1960) originally.

Intertrappean beds represent sediments that were deposited during pauses in the volcanic activity and variously coloured bole beds that formed after the weathering of the immediately underlying lava flows. Clayey or earthy red horizons are known to be intercalated in the flood basalts from several parts of the world, however their origin has been a matter of debate. Whatever may be the genetic modes of the bole beds, they provide us with a clearer understanding of chemical weathering processes and represent the weathering regimes in Deccan Basalts (Wilkins *et al.*, 1994). This is particularly true as the weathering profiles developed in the quiescence periods of the flood basalt eruptions can get preserved more easily between successive lava episodes. In this paper four intrabasaltic bole bed profiles occurring in the Yelapur area in Sangli district were studied in comparison with their underlying (parent) basalts to deduce the palaeoclimatic conditions during their formation.

(Received : 17 September 2021 ; Revised Form Accepted : 10 March 2022)

https://doi.org/10.56153/g19088-021-0057-3

Intrabasaltic Bole Beds and Palaeoclimates

According to Sayyed and Hundekari (2006) it is important to understand the terrestrial climatic events in unifying global climate change model and thus intrabasaltic bole beds have great potential in deducing the palaeoclimatic conditions (Sayyed, 2019).

Deccan trap basalts often contain variously coloured interflow bole beds which often separate the lava flows (Sayyed and Hundekari, 2006) however, there is no agreement in defining or understanding their origin (Mohapatra and Nair, 1996).These bole beds which represent a quiescence period during the Deccan volcanism are homogeneous, fine-grained clayey material showing a blocky cubical jointing but lack typical internal structures such as stratification or lamination (Duraiswami *et al.*, 2020). Sarkar and Sarkar (2015) used stable oxygen and carbon isotopes to unravel red boles formation mechanism and their results indicated that the alteration of basalts and pyroclastic material constitutes the plausible mechanism of red boles formation. As intrabasaltic bole beds are formed in direct exposure to climatic and related environmental conditions (Sheldon and Tabor, 2009; Sayyed, 2014; Sayyed *et al.*, 2014) and can be used as the potential tools in the reconstructions of terrestrial palaeoenvironments and palaeoclimates. The bole beds are clearly different from ferricretes and have received varied genetic interpretations (Duraiswami *et al.,* 2020). In characterizing Indian bole beds the petrographical investigations have not been attempted (Singh *et al.*, 2022) though in inferring the origin and palaeoenvironmental conditions such studies could be useful (Singh *et al.*, 2021). Dzombak *et al.* (2020), using the geochemistry of the bole beds, suggested limited influence of Deccan volcanism on K–Pg extinction.

Study Area

Sangli district is situated in the southeastern part of Maharashtra on Miraj-Karad highway and covers an area of 8572km^2, between latitudes 16°43'; 17°38'N and 73°41'; 75°41'E longitudes. Some of the important townships in the district are Tasgaon, Jath, Shirala, Kavathe Mahankal and Vite. For the present study four well preserved bole bed profiles from Shirashi, Karamale, Gavalewadi and Kinarewadi villages exposed in and around Yelapur area (located towards NW of Sangli) were selected for the detailed study (Fig. 1; Table 1).

Geology of the Study Area

Sangli district is covered extensively by the Sahyadri Group of Deccan Traps comprising of the Diveghat Formation, the Purandargarh Formation and the Mahabaleshwar Formation in the ascending order of succession of (GSI, 2001; Table 2). The Diveghat Formation consists of 10-12 flows of alternating Aa and Pahoehoe flows which vary in thickness from 5-35m while the Purandargarh Formation comprises essentially of seven simple flows some of which showing both Aa and mixed flow characters. The Mahabaleshwar Formation consists of nine Aa flows with thickness varying from 28m to 140m and are phyric in nature. Towards north and south of Tisangi village a patch of primary laterite having a thickness from 1.5m to 8m is exposed while along the banks of rivers, alluvium patches of about 10m thick are seen and mainly composed of pebbles, basaltic boulders, chert, silt and sand.

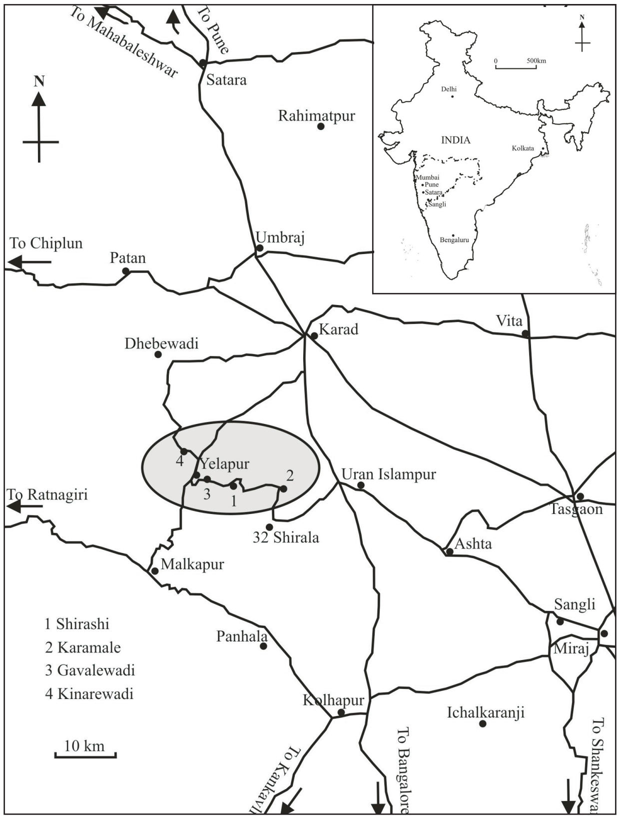

Fig.1. Location map of the study area and sampling stations

Table 1: Red bole bed profile locations in the study area

Formation	Profile Name	Co-Ordinates	Elevation
Purandargarh	Kinarewadi	17°06'12.60"N and 73°59'20.88"E	812m
	Gavalewadi	17°03'29.04"N and 74°01'30.00"E	718m
	Karamale	17°02'48.00"N and 74°08'46.62"E	693m
	Shirashi	17°03'12.42"N and 74°03'59.04"E	684m

Table 2: Lithostratigraphic scheme of classification of Deccan Traps from Western India (*After* Godbole *et al.,* 1996)

Super Group	Group	Sub Group	Formation	Thickness (m)
Deccan Traps	Sahyadri	Wai	Mahabaleshwar Purandargad	600
			Diveghat Karla	900
		Lonavala	Indrayani Ratangad	700
		Kalsubai	Salher	~1500

Field Investigations of the Bole Bed Profiles

The red bole beds and the associated lower (parent) basalts were systematically sampled. The profiles were prepared for the Purandargarh Formation covering its lowermost part at the Shirashi Section while the uppermost part at the Kinarewadi Section. The field characters of the red boles and their associated parent basalts at the four profiles are described with respect to their colour, vertical and lateral extent, contact details and other macro-morphology.

Shirashi Profile

The Shirashi Section (17° 03' 12.42"N and 74° 03' 59.04"E) is located on the way from Shirashi towards Yelapur exposes a distinct red bole bed with approximate thickness of 20cm (Fig. 2a). The bole bed shows sharp contact with the overlying highly weathered basalt and a gradational contact with the underlying very highly weathered basalt.

Karamale Profile

The Karamale Section is located on the way from Uran Islampur towards Yelapur (17° 02' 48.00"N and 74° 08' 46.62"E) and exposes red bole bed having an approximate thickness of 50cm (Fig.2b). This bole bed also shows sharp contact with upper weathered basalt and gradational contact with very highly weathered lower zeolitic basalt.

Gavalewadi Profile

The Gavalewadi Section is located towards west of the

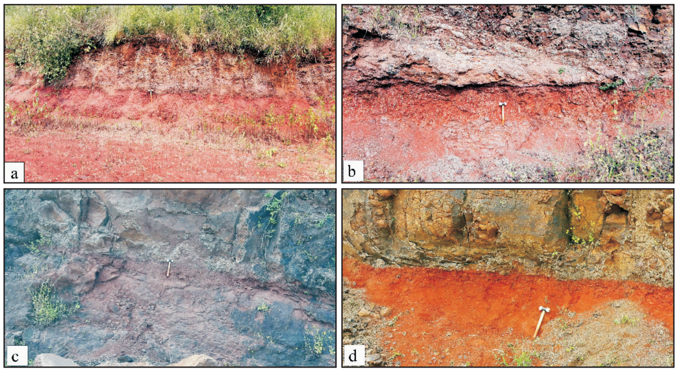

Fig.2. a. Red bole horizon from the Shirashi Section showing undulating sharp contact with the upper basalt and gradational contact with the lower basalt. b. Red bole horizon from the Karamale Section exhibiting a sharp contact with the jointed and compact upper basalt and gradational contact with the lower weathered zeolitic basalt. c. Red bole from the Gavalewadi Section showing sharp contacts with both the upper and lower compact basalts. d. Red bole from the Kinarewadi Section exhibiting sharp contact with the upper compact basalt and gradational contact with the lower zeolitic basalt.

Shirashi Section on the way from Uran-Islampur towards Yelapur (17° 03' 29.04"N and 74° 01' 30.00"E) and exposes approximately 40cm thick red bole horizon with a chocolate hue (Fig. 2c). The bole horizon also displays sharp contacts with the upper compact basalt and lower compact basalt.

Kinarewadi Profile

The Kinarewadi Section (17° 06' 12.60"N and 73° 59' 20.88"E) is located towards NW of the Gavalewadi Section which encloses red bole bed having approximate thickness of 70cm (Fig.2d). The bole bed is quite indurated with sheet joints as thin as 1cm having a sharp contact with the overlying spheroidally weathered basalt and gradational contact with very highly weathered zeolitic lower basalt.

Materials and Methods

The red bole samples along with their parent lower basalts were collected from the four bole bed profiles occurring around the Yelapur area. The samples collected were crushed to fine powder using agate mortar and pestle and homogenized by coning and quartering.

These ground samples were then analyzed for their major elements using AmetekXepos III X-ray fluorescence spectrometer (XRF) at Geology Department, Savitribai Phule Pune University. During XRF analysis for peak calibration glass tablets FLX-SP1 were used as standards while for global calibration FLX-SP2 were used. Ferrous iron concentrations (FeO) were estimated volumetrically using Pratt's method (Saikkonen and Rautiainen, 1993) while crystal lattice water (H_2O^+) contents were determined by using the method given by Davies (1974).

Results

From the geochemical data (weight % element oxides) of the boles beds and the associated underlying parent basalts various weathering indices were computed using the molecular proportions of the major element oxides (Table 3) which were used in the interpretations of palaeoweathering conditions.

Chemical Index of Weathering (CIW)

Weathering indices like CIA (Nesbitt and Young, 1982) and PWI (Parker, 1970) use K_2O as mobile component. The CIW index (Harnois, 1988) avoids problems related to the remobilization of K during digenesis or metamorphism limiting its application to soils and palaeosols in which potassium has been actually leached.

$$\text{Chemical Index of Weathering} = \frac{100 \text{ X } (Al_2O_3)}{(Al_2O_3 + CaO^* + Na_2O)}$$

Where CaO* is the amount of CaO from the silicate fraction of the rock.

The CIW values for the bole beds (Fig. 3a) suggest intermediate chemical weathering (CIW values between 60 and 80) with removal of mobile cations ($Ca^{2+}$and Na^+) relative to immobile constituent (Al^{3+}) during the process of chemical alteration. This can be attributed to comparatively moderate temperature and rainfall during the formation of red boles from their respective parent lower basalts.

Parker's Weathering Index (PWI)

Based on the most mobile elements (*i.e.* alkali and alkaline earth metals) of the major elements Parker (1970) introduced the Parker's Weathering Index using the bond strengths of these elements with oxygen (Nicholls, 1963) as weighting factors in the index.

$$\text{Parker' s Weathering Index} = 100 \text{ X} \left[\left(\frac{Na^*}{0.35} \right) + \left(\frac{Mg^*}{0.9} \right) + \left(\frac{K^*}{0.25} \right) + \left(\frac{Ca^*}{0.7} \right) \right]$$

In general the fresh parent rock have higher PWI value and hence more susceptible to weathering than its weathered product

Table 3: Major element oxide (weight %) and weathering indices for red boles and associated lower basalts from the study area.

Profile	Shirashi		Karamale		Gavalewadi		Kinarewadi	
Elevation	684m		693m		718m		812m	
Sample Type	Lower Basalt	Red Bole	Lower Basalt	Red Bole	Lower Basalt	Red Bole	Lower Basalt	Red Bole
Sample No.	F1	F2	F3	F4	F5	F6	F7	F8
SiO_2	47.20	51.00	46.00	49.60	47.40	40.50	44.00	50.40
Al_2O_3	15.10	12.90	15.30	12.50	13.90	15.70	14.10	12.50
FeO	0.40	0.12	0.64	0.24	0.40	0.16	0.80	0.24
Fe_2O_3	16.90	16.50	17.60	15.80	15.50	24.60	17.90	16.00
MnO	0.30	0.31	0.29	0.31	0.19	0.26	0.16	0.31
MgO	3.58	4.44	3.09	5.53	4.12	1.98	3.95	4.35
CaO	3.58	2.59	3.30	2.92	5.71	2.48	4.26	2.55
Na_2O	0.15	0.05	0.05	0.05	0.09	0.06	1.24	0.05
K_2O	0.02	0.37	0.01	0.03	0.53	0.17	0.22	0.36
TiO_2	3.74	2.77	3.86	2.96	3.29	4.11	4.97	2.70
P_2O_5	0.01	0.02	0.48	0.06	0.21	0.08	0.36	0.02
H_2O^+	8.88	8.42	9.48	9.06	8.74	9.21	7.82	10.50
Total	99.80	99.40	100	99.00	100	99.20	99.70	100
CIW	69.03	72.83	71.57	69.96	56.91	77.30	58.90	72.46
PWI	19.81	20.68	17.23	23.08	28.55	12.76	28.40	20.32
MAT	---	16.61	---	17.14	---	16.96	---	16.57
MAP	---	928	---	877	---	1014	---	922
ISR	18.84	58.80	12.25	29.05	17.65	71.69	10.02	30.11
PI	72.03	76.21	70.73	75.93	73.84	65.14	69.42	76.40
Hydrolysis	---	0.78	---	0.64	---	1.59	---	0.77
Salinization	---	0.04	---	0.01	---	0.02	---	0.04
$AI_{\text{Köppen}}$	---	18.71	---	17.50	---	20.29	---	18.59

which would have lower index value. Except the Karamale profile, the red boles from the other three profiles show lower PWI values (Fig. 3b) than their respective parent basalts indicating their less susceptibility to further weathering as compared to their parent basalts.

Mean Annual Temperature (MAT)

Sheldon *et al.* (2002) found a potentially useful relationship between molecular ratio of alkalies to alumina and the MAT which they used to calculate the MAT with the following equation.

$$\mathrm{MAT} = 18.516(\mathrm{S}) + 17.298, \quad \text{Where S}= \frac{(\mathrm{K_2O + Na_2O})}{(\mathrm{Al_2O_3}\ )}$$

The MAT values for red boles (Fig. 3c) do not show much variations (between 16.57°C and 17.14°C) suggesting that the conditions during their formation were not much warm.

Mean Annual Precipitation (MAP)

Sheldon *et al.* (2002), using the exponential fit, found the strongest relationship between the MAP and the chemical index of alteration without K (CIA-K) to calculate the MAP as under

$$\mathrm{MAP\,(mm)} = 221e^{(0.0197\,(\mathrm{CIA-K})}$$

$$\text{Where CIA-K} = 100 \text{ X } \frac{(\mathrm{Al_2O_3})}{(\mathrm{Al_2O_3 + CaO^{*} + Na_2O})}$$

Higher rainfall gives higher CIA-K values which normally lead to more intense chemical weathering resulting in preferential removal of mobile elements and enrichment of refractory elements. The MAP values obtained for the red boles (Fig. 3d) do not show much variations (877mm - 1014mm) and indicate their formation under moderate rainfall (not much wet condition).

Iron Species Ratio (ISR)

In most rock-forming minerals iron is present in ferrous state (reported as FeO) which on chemical weathering under oxidizing environment gets converted to ferric state (reported as Fe_2O_3) resulting in increase in Fe_2O_3/FeO ratio in a weathering profile. In order to determine the degree of oxidation (or reduction) during chemical weathering iron species ratio is commonly used which is given by the following equation.

$$\text{Iron Species Ratio} = \frac{\mathrm{Fe_2\,O_3}}{\mathrm{FeO}}$$

The high Iron Species Ratio (29.05 to 71.69) in red boles (Fig.3e) from all the four profiles suggests oxidizing conditions prevailed during their formation.

Product Index (PI)

Reiche (1950) defined product Index (PI) which decreases slowly with the loss of silica in the weathering environments.

$$\text{Product Index} = 100 \text{ X } \frac{\mathrm{SiO_2}}{\mathrm{SiO_2 + TiO_2 + Fe_2O_3 + FeO + Al_2O_3}}$$

From the PI values (Fig. 3f) it is seen that in the red boles, except from the Gavalewadi profile, there is a relative increase in the silica content as compared to the respective lower basalt. This implies that the weathering conditions were not favourable for leaching of silica during red bole formation and hence point towards rather acidic conditions.

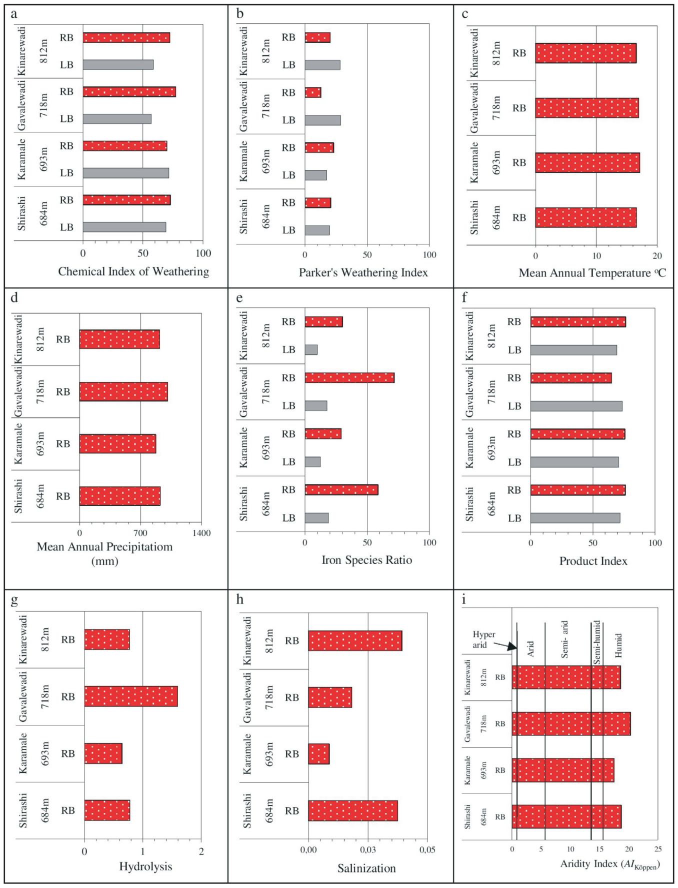

Fig.3. Weathering indices for the rocks from the study area.

Hydrolysis

Chemical weathering is facilitated by combination of carbon dioxide with water (producing weak carbonic acid) which is the most fundamental to chemical weathering conditions because of the existence of water (in air and on the surface), abundant oxygen and presence of carbon dioxide on the surface.

$$\mathrm{H_2O + CO_2} \dashrightarrow \mathrm{H_2CO_3} \text{ then, } \mathrm{H_2CO_3} \dashrightarrow \mathrm{H^+ + HCO_3^-}$$

The available rainfall and temperature increases the chemical weathering intensity by hydrolysis because precipitation and temperature hasten the leaching of alkali and alkaline earth elements. Retallack (2001) devised the hydrolysis ratio by using the fact that with progressive weathering of silicate minerals the base cations are lost relative to Al which results into formations of clay minerals.

$$\text{Hydrolysis} = \frac{\mathrm{Al_2O_3}}{\mathrm{CaO + MgO + Na_2O + K_2O)}}$$

Except the Gavalewadi profile, the values of hydrolysis ratio in the red boles (Fig. 3g) are considerably similar (the values for all the four boles are less than 2 which is typical of alfisols) suggesting relatively less leaching owing to moderately wet and less warm climatic conditions during their formation as revealed from the values of the MAP and the MAT.

Salinization

Salinization indicates the abundance of salts within any soil profile which is calculated by using a formula ($Na_2O + K_2O$) /Al_2O_3 (Retallack, 2001) that also measures evaporation, precipitation (Sheldon and Tabor, 2009) and water accumulation. Evaporation exceeding precipitation is indicated by high values of salinization while a well-drained condition is shown by low values where saline conditions do not develop. The significant salinization is indicated by a threshold value of 1 as sodium is generally more soluble than potassium and also less affected by digenetic processes (Retallack 1991).Very low values of salinization (0.01 to 0.04) from all the four red boles (Fig. 3h) suggest their formation under well drained conditions removing the mobile alkali elements (Na^+ and K^+).

Aridity Index

Quan *et al.* (2013) after validating five widely used precipitation-temperature (P-T) based aridity indices, demonstrated that AI_{Koppen} is the most reliable index. The application of AI_{Koppen} (Koppen, 1923) in palaeoclimate studies requires only two climatic parameters (MAT and MAP) and is calculated according to following formula

$$AI_{Koppen} = \frac{MAP}{(MAT+33)}$$

The values of AI_{Koppen}aridity index (Fig. 3i) suggest that all the four red boles were formed under semi-humid to humid conditions.

A-CN-K Ternary Plot

The chemical weathering is mostly evaluated by using simple calculated value of the chemical weathering indices. However, $Al_2O_3-(CaO^*+Na_2O)-K_2O$ ternary plot (A−CN−K plot) is used by many (Nesbitt and Young, 1989; Roddaz *et al.*, 2006; Raza *et al.*, 2011) to compare the chemical weathering trends. A-CN-K Ternary plot (Nesbitt and Young, 1989) shows the molar proportions of Al_2O_3 (A apex), $CaO^*+ Na_2O$ (CN apex) and K_2O (K apex), where CaO* denotes CaO bound in the silicate minerals. In igneous rocks the weathering trends are initially sub parallel to CN−A join as from plagioclases Ca^{++} and Na^{++} are removed from the weathering profile and resulting enrichment of Al^{+++}in the weathered residues leading to formation of clay minerals. The weathering trends as depicted in the A-CN-K diagram (Fig. 4a) indicates that the parent basalts from the four profiles have undergone some chemical alteration while plots of red boles show removal of CaO, Na_2O and K_2O from their parent basalts with concomitant enrichment of Al_2O_3thus showing weathering trend towards smectite formation.

Lateritization

Schellmann (1986) suggested a triangular diagram (SiO_2 - Fe_2O_3 - Al_2O_3) to ascertain the extent of lateritization by comparing the extent of chemical alteration of a weathering product (within a weathering profile) to the composition of the parent rock in order to define 'degree of lateritization' (Widdowson, 2009).The extent of lateritization can be plotted on this triangular diagram which recognizes four stages of lateritization process *viz.* a) kaolinization, b) weak lateritization, c) moderate lateritization and d) strong lateritization.

The chemical data plotted for the rocks from four bole bed profiles (Fig. 4b) reveals that none of the profiles show any lateritization but have reached only kaolinization stage.

Discussion

The sub-aerial weathering of the parent basalts in most of the continental flood basalt provinces has resulted in a concomitant development of the palaeosols, representing the well-defined inter-eruptive time intervals. They are often seen to be sandwiched between the slightly weathered to fresh basalt flows, when compared in terms of the degree of weathering. To deduce the palaeoweathering and palaeoclimates during such volcanic episodes intrabasaltic palaeosols are widely used in recent past (Ghosh *et al.*, 2006; Hill *et al.*, 2000; Sheldon *et al.*, 2002; Sheldon, 2002, 2003; Sayyed and Hundekari, 2006; Solleiro-Rebolledo *et al.*, 2003; Tabor *et al.*, 2004; Widdowson *et al.*, 1997) as climatic effects of the flood basalts are often considered to be severe and that there is a casual link between flood basalt, climates and mass extinctions. During the Deccan volcanism many volcanic quiescence periods were recorded which were due to discontinuous and episodic eruptive process and have been marked by many intrabasaltic sedimentary and weathering regimes including the bole bed horizons generally less than a meter in thickness. As such bole beds represent the chemical weathering processes which were operative during the quiescence periods between two successive lava flows they are used to calculate the time gap between the consecutive lava flows in the Deccan traps (Gerard *et al.,* 2006). The

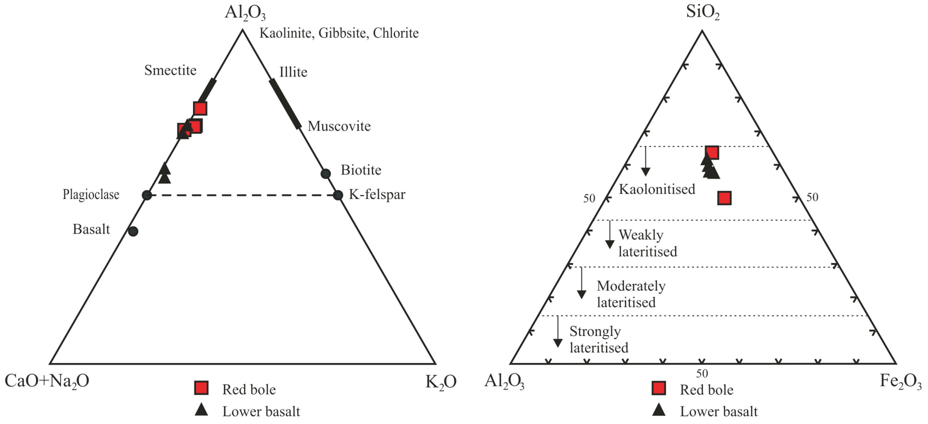

Fig.4. a. A-CN-K Plot for the rocks from the study area, b. Lateritization diagram for the rocks from the study area.

red boles in the Deccan basalts formed during the quiescence periods preserve the palaeoweathering characters (Wilkins *et al.*, 1994; Widdowson *et al.*, 1997) and hence, they are also considered to have been formed by the pedogenesis of the underlying lava flows (Ghosh *et al.*, 2006; Sayyed and Hundekari, 2006). The bole beds, in the mainland of the Deccan Volcanic Province, are generally intertrapped between only slightly weathered lower basalts and almost fresh, un-weathered upper basalts. Thus the bole beds are certainly the weathering residue of the basalts and hence can be used in deducing the palaeoenvironment of their formation. Sheldon (2003), however, has put forth a fundamental question that whether such intrabasaltic palaeosols can be used reliably in deducing the palaeoenvironmental conditions as they could have been altered by baking or metasomatism. Detailed studies on such intrabasaltic palaeosols from different flood basalt provinces of the world have so far revealed the vital palaeoclimatic information.

Conclusions

The geochemical characters of the red boles and their associated parent basalts suggest the distinctive palaeoclimatic conditions during the bole bed formation. The red boles were formed as a result of intermediate chemical weathering of their parent basalts under humid to sub-humid conditions. The moderate rainfall and moderately warm climatic conditions are also conducive for the formation of the red boles. A well-drained conditions can be envisaged under acidic and oxidizing environment. The red boles are less susceptible to further chemical weathering as compared to their parent basalts. All the red boles show their weathering trends towards smectite formation without any lateritization as they have reached only kaolinization stage.

Authors' Contributions

M.M. Shaikh: Conceptualization, Methodology, Software, Drafting. **M.R.G. Sayyed.**: Data Curation, Visualization, Supervision, Editing**. D.C. Meshram**: Field Study, Sampling Methods.

Conflict of Interest

The authors declare that they have no conflict of interest.

Acknowledgements

The authors gratefully acknowledge the department of chemistry, Poona College, Pune and Abeda Inamdar College, Pune for providing laboratory facilities. Thanks are also due to the Principal, Poona College and Head, Geology Department, Savitribai Phule Pune University for their constant support in carrying out this research work. Authors also express sincere thanks to the anonymous reviewers and the Editor of the JGSR.

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