Palaeoweathering characteristics of an intrabasaltic red bole of the Deccan Flood Basalts near Shrivardhan of western coast of India

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An intrabasaltic red bole horizon is studied for its weathering characteristics with respect to the underlying and overlying basalts. The study indicates that all the three units have been considerably weathered; the red bole unit, however shows some distinctive characteristics. The red boles show a higher cation exchange capacity (CEC) and lower sodium adsorption ratio (SAR) and organic carbon (OC) as compared to the weathered basalts. The lower values of Al_2O_3 , TiO_2 and $\text{Fe}_2\text{O}_3(\text{T})$ in red boles indicate their lesser weathering than the underlying and overlying basalts, which is further corroborated by the weathering intensity measured by the indices like chemical index of alteration (CIA) and statistical empirical index of chemical weathering (W). It is also evident that the red bole samples show more retention of original mafic and felsic components. While K_2O exhibits an erratic behaviour, the MgO and CaO do not show much leaching in red boles. Lesser leaching and salinity in the red boles is indicated by the higher values of calcification and lower values of salinization. The $\text{SiO}_2\text{--Al}_2\text{O}_3\text{--Fe}_2\text{O}_3$ plot indicates that red bole samples are close to the basalt field, while the weathered upper basalt is more kaolinized than the weathered lower basalt. These observations reveal that the post-formational weathering processes have least affected the original palaeoweathering characters of the red bole horizon and hence the intrabasaltic palaeosols (weathering horizons) can effectively be used to constrain the palaeoweathering and palaeoclimates during the continental flood basalt episodes in the geologic past.

1. Introduction

Large igneous provinces (LIPs) covering millions of square kilometers of the earth surface (Coffin and Eldholm 1994) have been widely distributed, both spatially and temporally, amongst which some are submarine and others are terrestrial (Jerram and Widdowson 2005). The question is whether or not these eruptions changed the climate leading to the mass extinctions, as many considered the Continental Flood Basalt Volcanism responsible for most extinction events (McLean 1985; Courtillot 1990;

Courtillot *et al.* 1996). The comparison of the ages of flood basalt provinces and mass extinction events (Wignall 2001) provide the most compelling evidence for a link between volcanism and extinctions. Since the chemical weathering is a response to the contemporaneous reactions between the meteoric water equilibrated with the atmospheric gases and the protoliths, ancient soils have been largely used to understand the palaeoclimates. Clayey or earthy red horizons are known to be intercalated in the flood basalts from several parts of the world although their origin has been a matter of debate.

Keywords. Bole beds; palaeosol; palaeoclimates; palaeoweathering; geochemistry; Deccan Traps.

Some describe them as meteoric weathering products (palaeosols) or saprolites and others consider them to be formed as a result of the hydrothermal alteration of basalt. In the case of bole horizons from the Deccan Volcanic Province, there are different views regarding their origin and the following origins have been suggested:

- Intertrappean sediments (Fermor 1927; Pascoe 1973);
- weathered products of basalts (Lyell 1958; Agashe and Gupte 1968);
- submarine pelagic deposits (Shepard 1963; Inamdar and Darshan Kumar 1994); and
- weathered pyroclastics (Wilkins *et al.* 1994; Mohapatra and Nair 1996).

Irrespective of the origin of the bole beds, the above information creates an understanding of the chemical weathering processes of Deccan basalts under different weathering regimes (Wilkins *et al.* 1994) irrespective of their genetic modes. This is particularly true when the weathering profiles developed in the quiescence periods of the flood basalt eruptions can get preserved more easily between successive lava episodes. Therefore, such continental palaeoweathering records with strong mineralogical and geochemical fingerprints are immensely important to understand the global palaeoclimates (Widdowson 1997a, b; Thiry *et al.* 1999). In the present study, an intrabasaltic bole bed developed during the Maastrichtian ($\cong 65$ Ma) Deccan Volcanic Episode was studied in relation to the overlying and underlying basalts.

2. Intrabasaltic bole beds and palaeoclimates

Palaeoclimatic records are necessary in predicting the future climatic changes on the earth as these unveil the changes in the atmospheric chemistry and the response of natural systems. There were periods when the climates were significantly cooler and warmer than the present, as recorded in the earth's history, in response to the globally distributed climate change events, which affected the oceanic, atmospheric, and terrestrial events. These periods offer a unique opportunity in modelling and predicting the global climate response to enhanced greenhouse gases as the variations in the atmospheric carbon dioxide concentrations are now linked, on almost every timescale, to extreme past climate change record (global cooling to global warming). Thus in order to develop a unifying global climate change model it is important to understand the terrestrial events as well (Sayyed and Hundekari 2006). The study

of palaeosols carries great potential as their mineralogy, chemistry, and weathering pattern can be used in inferring the palaeoclimatic conditions. Further, the interpretative value of basalt-derived palaeosols is increased because of the fairly homogeneous nature of the basaltic parent-material and also, the palaeosol characteristics can be related to contemporary soil genesis from basalt. Thus intrabasaltic palaeosols provide high-resolution palaeoclimatic records of terrestrial environment if the ages of the associated basalt flows can be determined.

3. Area of study

Shrivardhan is an important township in the Raigad district of Maharashtra state in India. This region is an important part of Deccan Volcanic Province as it is supposed to have been affected by the flexure folding and other post-Deccan Trappean tectonic disturbances. Physiographically, the area is remarkably flat forming a narrow strip of coastal land where the climate is characterized by mean annual rainfall of about 3000 mm, hot weather in summer (March to May), and high humidity throughout the year. In May (the hottest month of the year), the daily mean maximum temperature is 31.7°C and the daily mean minimum temperature is 26.4°C. As this area experiences relatively high rainfall characteristic of a humid climate, the basaltic flows here are subjected to intensive weathering as evidenced by the presence of bauxitic and lateritic rocks carrying the signatures of intensive chemical leaching. Towards the east of Shrivardhan (on the way to Mumbai-Goa highway, near Sai village, figure 1) a red bole horizon (figure 2) is seen exposed between two basaltic flows. Both overlying and underlying basalts are extensively weathered as in other part of Deccan Traps basalts intercalating the bole beds are relatively fresh. In order to examine the use of flood basalt intercalated bole beds as palaeoclimatic proxy the whole section was studied and the results are presented.

4. Methods of study

The bole beds and the weathered basalt samples were crushed and powdered to analyze their major element compositions using X-ray fluorescence (Balaram *et al.* 1999). The crystal lattice water (H_2O^+) was determined by heating the rock samples at 600°C in an oven for about six hours. The major elemental analysis data are presented as weight percent oxides. Certain physical and chemical parameters like sodium adsorption ratio (SAR),

Figure 1. Location map of the study area.

cation exchange capacity (CEC), and organic carbon (OC) were estimated for bole beds and weathered basalts using the procedures given by Trivedi *et al.* (1987). The SAR, CEC, and OC may provide information about the nature of the environment with respect to chemical and biological activity. To understand the palaeoweathering of the bole beds and present day weathering of overlying and underlying basalts, various weathering indices were calculated. These indices were calculated from the molecular percent data (recalculated from weight percent data) since the stoichiometric proportions of various elements are commonly more informative in weathering studies than the weight percentages (Reiche 1943). The geochemistry of Sai bole beds was compared with the bole beds occurring elsewhere in the mainland of the Deccan traps (table 2). The rare earth elements analysis is presented in table 3.

5. Results

Red bole samples show CEC higher than the underlying and overlying weathered basalts (table 1; figure 3a) and the SAR and OC values are more for weathered basalts (figure 3b and c). CEC depends upon the amount and type of clay and organic matter present in the soil; clay rich soils with more organic matter usually have higher CEC. Figure 3(a) suggests that the red bole samples from both the profiles are clay rich and show higher CEC values than the weathered basalts. SAR shows the relative proportion of Na^+ ions as compared to Ca^{++} and Mg^{++} ions. Figure 3(b) indicates that the bole beds have lesser amount of exchangeable sodium (lower SAR) in contrast to the weathered basalts. The Al_2O_3 , TiO_2 , and $\text{Fe}_2\text{O}_3(\text{T})$ values are lower in red boles than in the weathered basalts (figure 4a, b and c). Chemical index of alteration

a: Profile 1

b: Profile 2

Figure 2. An intrabasaltic red bole horizon showing weathered overlying and underlying basalts.

(CIA) values (Nesbitt and Young 1982) and statistical empirical index of chemical weathering (W) values (Ohta and Arai 2007, figure 5a and b) are lower for red boles than the weathered basalts. The red boles also indicate more retention of original felsic and mafic components (figure 5c and d). Amongst alkali and alkaline earth metal oxides (figure 6a, b and c) K_2O shows erratic distribution and MgO and CaO are extensively leached from the weathered basalts. In the SiO_2 – Al_2O_3 – Fe_2O_3 triangular diagramme (Schellmann 1986) (figure 7) it is evident that the red boles are least weathered (close to basalt) and the overlying basalts are most weathered (highly kaolinized). Retallack (2003) devised measures to reflect hydrolysis [$Al_2O_3/(CaO+MgO+Na_2O+K_2O)$], calcification [$(CaO+MgO)/Al_2O_3$], and salinization (Na_2O/K_2O) with the advantages of their simplicity and precision, free from assumptions concerning parent material composition, and changes in

volume during weathering and burial compaction. The computation of these indices shows that red boles show higher calcification (lesser leaching) and lower salinization (figure 8a and b) as compared to the associated basalts. The values of mean annual precipitation (MAP) and mean annual temperature (MAT) have been calculated by the formulae given by Sheldon *et al.* (2002) which are as follows:

$$MAP \text{ (mm)} = -259.34 \ln(B) + 759.05$$

where B = molar ratio of bases to alumina

$$MAT(^{\circ}C) = -18.516(S) + 17.298$$

where S = molecular ratio of Na_2O and K_2O to Al_2O_3 .

6. Discussion

The emplacement of Deccan Trap lava flows was not a continuous process and the volcanic quiescence periods have been recorded by many intrabasaltic weathering and sedimentary horizons including the bole beds which are generally less than one meter thick. Bole beds bear witness to the processes occurring between emplacements of two successive lava flows and hence they can be effectively used to constrain the time intervals between the successive lava flows in the Deccan traps (Gerard *et al.* 2006). The red boles in the Deccan basalts, characteristically formed during the quiescence period of the fissure eruptions, have been considered as palaeosols as the palaeoweathering characters of the bole beds indicate that they are the weathered products of the parent basalts (Wilkins *et al.* 1994; Widdowson *et al.* 1997). Ghosh *et al.* (2006) and Sayyed and Hundekari (2006) in their recent studies concluded that Deccan bole beds are the paleosols which are formed by the pedogenesis of the underlying lava flows. In the mainland of Deccan Volcanic Province, generally the bole beds are sandwiched between only slightly weathered lower basalts and almost fresh, unweathered upper basalts. Thus, the bole beds are definitely the weathered products of the basalts and hence indicate the palaeo-environment of their formation. In the study area, it was found that even the upper basalt along with lower basalt has been extensively weathered. The physico-chemical and geochemical characteristics of red bole horizons (figure 2) demonstrate that the red boles are conspicuously distinct from the underlying and overlying weathered basalts. The higher values of Al_2O_3 , TiO_2 , $Fe_2O_3(T)$, CIA, and W indicate that the basalts are more weathered than the red boles. Higher retention of felsic and mafic components of the original basalt;

Table 1. Composition and selected parameters of the red boles and associated basalts.

	Profile 1					Profile 2				
	UB1	RB1	RB2	RB3	LB1	UB2	RB4	RB5	RB6	LB2
Depth (m)	0.70	0.90	1.11	1.40	1.60	0.45	0.67	0.84	1.07	1.22
SiO ₂	36.25	43.48	43.35	43.71	41.04	37.60	44.79	43.98	43.80	40.25
TiO ₂	2.90	2.14	2.09	2.09	2.43	2.77	2.07	2.09	2.10	2.51
Al ₂ O ₃	17.08	12.81	12.88	12.13	15.41	18.16	12.48	12.33	12.11	16.49
Fe ₂ O ₃	21.55	17.41	17.28	17.33	18.90	19.97	17.25	17.09	17.63	17.31
MgO	3.11	4.86	4.96	4.71	4.18	3.04	4.88	5.24	4.89	4.07
CaO	0.77	1.54	1.51	1.48	1.23	0.77	1.55	1.64	1.55	1.12
Na ₂ O	0.0008	0.0008	0.0008	0.0008	0.0009	0.0008	0.0009	0.0008	0.0008	0.0008
K ₂ O	0.12	0.40	0.32	0.68	0.32	0.09	0.15	0.19	0.63	0.19
H ₂ O ⁺	17.97	17.15	17.56	17.83	16.46	17.56	16.81	17.42	17.01	17.83
Total	99.75	99.79	99.95	99.96	99.97	99.96	99.98	99.98	99.72	99.77
Salinization	0.0071	0.0021	0.0026	0.0012	0.0027	0.0091	0.0056	0.0043	0.0013	0.0045
Calcification	0.23	0.50	0.50	0.51	0.35	0.21	0.51	0.56	0.53	0.31
Mafic components	3.28	4.46	4.73	3.68	3.66	3.35	6.20	6.20	3.96	3.91
Felsic components	0.00	0.01	0.01	0.02	0.01	0.00	0.01	0.01	0.02	0.01
W	84.98	53.87	54.23	54.37	64.35	84.89	52.77	51.31	53.22	67.48
CIA	95.04	86.80	87.50	84.88	90.88	95.48	88.02	87.03	84.75	92.65
Organic carbon	4.42	3.56	2.10	3.39	3.61	5.81	4.32	2.46	1.65	4.35
CEC	80.90	208.05	189.80	175.70	130.30	61.80	208.80	201.15	172.30	105.60
SAR	0.40	0.25	0.26	0.20	0.24	0.46	0.26	0.19	0.26	0.35

UB: Upper basalt; RB: Red bole; LB: Lower basalt.

Figure 3. Variations of cation exchange capacity, sodium adsorption ratio and organic carbon.

Figure 4. Variations of Al₂O₃, TiO₂ and Fe₂O₃(T).

Figure 5. Variations of chemical index of alteration (CIA), empirical statistical index of weathering (W), felsic components and mafic components.

Figure 6. Variations of K₂O, MgO and CaO.

higher concentration of CaO and MgO; and higher calcification and lower salinization in the red bole samples further support the theory that the red boles are less weathered. The SiO₂–Al₂O₃–Fe₂O₃ (figure 7) plot also clearly shows that the red boles are least weathered as compared to the upper basalts. The REE studies suggest that the red boles were not recycled and they are *in-situ* products of basalt weathering.

The geochemical comparison of the Sai red boles with those occurring in the mainland of Deccan Traps has been attempted (table 2) to constrain the effects of post-formational processes on the bole beds. Deccan Trap bole beds are the weathering products of the basalts and hence they show higher weathering characteristics than the parent underlying (weathered) basalts. At the same time the overlying basalts are quite fresh and relatively unaltered which clearly indicates fairly good preservation of the bole beds from the post-formational processes like weathering, diagenesis, or metasomatism. When the Sai red boles are compared with other Deccan Trappean bole beds with

Figure 7. SiO₂–Al₂O₃–Fe₂O₃ triangular plot indicating extent of lateritization (after Schellmann 1986).

the help of geochemistry it was found that Sai red boles show higher hydrolysis and lower calcification (figure 9a); extensive leaching of bases (figure 9b); and considerably higher weathering intensity (figure 9c) than other Deccan bole beds. Further, the mean annual precipitation (MAP) values for Sai red boles are lower (figure 9d) with higher mean annual temperature (MAT) values than other Deccan boles. All these observations indicate that the Sai red boles have been more altered than the rest

of the bole beds, which can be ascribed to the post-formational processes, especially chemical weathering and leaching of bases. However, it is also evident (figure 5) that the lower and upper basalts from Sai have been quite extensively weathered as compared to the Sai red boles which is unusual, as other Deccan Trappean bole beds invariably show higher weathering characteristics than the associated basalts. Further, it is also evident that Sai upper basalts show extensive weathering (higher than lower basalt) which is also unusual as compared to other Deccan upper basalts. Hence, it can be said that the whole red bole profile (including associated basalts) from Sai has been affected by post-formational processes. However, the red boles have been least affected while associated basalts (especially upper basalt) were undergoing significant and rather extensive chemical weathering during the Holocene.

From the extensive studies on the behaviour of rare earth elements (REEs) during weathering (see Laveuf and Cornu 2009 and references therein), it has been found that the REE stock generally decreases with an increase in weathering. The upper part of weathering profiles show general depletion of REEs and the bottom part of the profile may, some times, get enriched with REEs possibly due to their reprecipitation (Braun *et al.*

Figure 8. Variations of calcification and salinization.

Table 2. Molecular weight percent data for the bole beds and the associated basalts.

	Deccan bole beds					Sai red boles						Sai lower	Sai upper		
	#	#	\$	μ	$\S$	Present study						basalt	basalt		
	PRB	PGB	ARB	SGD	IB	RB1	RB2	RB3	RB4	RB5	RB6	LB1	LB2	UB1	UB2
SiO ₂	49.31	55.67	42.40	43.21	43.86	43.68	43.40	43.75	44.82	43.98	44.08	41.08	40.49	36.50	37.64
TiO ₂	2.31	1.88	2.23	2.12	1.97	2.14	2.09	2.09	2.07	2.09	2.10	2.43	2.51	2.90	2.77
Al ₂ O ₃	12.16	10.07	13.97	13.03	12.07	12.81	12.88	12.13	12.48	12.33	12.11	15.41	16.49	17.08	18.16
Fe ₂ O ₃ (T)	18.11	15.11	14.66	15.61	15.11	17.41	17.28	17.33	17.25	17.09	17.63	18.90	17.31	21.55	19.97
MgO	4.95	5.64	4.05	4.67	4.57	4.86	4.96	4.71	4.88	5.24	4.89	4.18	4.07	3.11	3.04
CaO	2.74	2.42	4.98	4.58	4.18	1.54	1.51	1.48	1.55	1.64	1.55	1.23	1.12	0.77	0.77
Na ₂ O	0.09	0.06	0.54	0.39	0.33	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
K ₂ O	0.68	1.76	1.75	0.46	0.45	0.40	0.32	0.68	0.15	0.19	0.63	0.32	0.19	0.12	0.09
H ₂ O ⁺	9.37	7.12	15.03	15.67	16.55	17.15	17.56	17.83	16.81	17.42	17.01	16.46	17.83	17.97	17.56
Total	99.72	99.73	99.61	99.74	99.09	100	100	100	100	100	100	100	100	100	100
CIA	67.41	61.05	54.09	57.92	58.27	86.80	87.50	84.88	88.02	87.03	84.75	90.88	92.65	95.04	95.48
Bases/R ₂ O ₃	0.69	0.94	0.85	0.83	0.84	0.59	0.59	0.60	0.59	0.64	0.61	0.43	0.41	0.27	0.27
SiO ₂ /R ₂ O ₃	3.15	4.28	2.76	2.86	3.08	2.79	2.78	2.88	2.92	2.89	2.88	2.29	2.24	1.80	1.86
Hydrolysis	0.66	0.48	0.63	0.61	0.59	0.82	0.82	0.79	0.81	0.74	0.76	1.16	1.31	1.80	1.96
Calcification	1.45	1.87	1.39	1.55	1.60	1.19	1.20	1.21	1.22	1.33	1.26	0.84	0.75	0.55	0.50
Salinization	0.20	0.05	0.47	1.30	1.11	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.01	0.01
Product index	75.88	81.07	73.37	74.10	75.49	73.60	73.53	74.21	74.47	74.28	74.22	69.56	69.14	64.25	65.02
MAP	880	914	884	888	894	811	812	822	814	836	831	—	—	—	—
MAT	15.74	14.44	13.57	15.68	15.72	16.66	16.79	16.17	17.05	16.98	16.25	—	—	—	—

Sayyed and Hundekari (2006) and Ghosh *et al.* (2006); \$ Inamdar and Darshan Kumar (1994); μ Widdowson *et al.* (1997); $\S$ Wilkins *et al.* (1994). PRB (Pune Red Boles); PGB (Pune Green Boles); ARB (Akola Red Boles); SGD (Sinhgad Red Boles); IB (Average Indian Boles).

Table 2. (Continued.)

	Sayyed and Hundekari (2006) and Ghosh et al. (2006)												
	Deccan lower basalts					Deccan upper basalts							
	A2	F2	G1	H2	I2	A1	B1	D1	E1	F1	G2	H1	I1
SiO ₂	49.63	48.72	51.23	47.74	50.99	52.81	49.65	50.06	50.32	54.17	50.22	48.45	49.56
TiO ₂	3.24	3.97	2.54	3.45	2.44	2.29	2.16	2.1	2.92	2.19	1.96	3.24	2.02
Al ₂ O ₃	11.22	12.2	14.67	14.14	12.87	16.96	13.83	13.44	12.87	15.84	15.2	15.14	14.07
Fe ₂ O ₃ (T)	16.91	15.75	14.70	19.09	14.49	8.04	12.42	15.12	15.91	10.51	14.22	16.84	13.73
MgO	5.6	5.27	4.79	5.11	6.39	4.52	7.22	5.73	5.29	5.18	5.58	4.76	6.25
CaO	7.34	5.88	6.69	3.34	10.11	5.7	9.17	10.51	9.86	7.5	9.77	6.07	11.33
Na ₂ O	1.38	1.36	1.4	0.42	1.64	1.84	1.64	2.25	2.29	1.94	1.9	1.17	2.1
K ₂ O	0.71	0.93	1	0.19	0.27	3.88	0.3	0.25	0.27	1.75	0.53	0.22	0.39
H ₂ O ⁺	3.5	5.81	3.38	6.28	0	3.55	3.13	1.23	0.52	1.07	1.08	2.89	0.56
Total	99.62	100.32	100.63	99.88	99.46	99.85	99.61	100.28	100.12	100.29	100.25	99.14	100.08
CIA	40.61	46.64	48.51	66.95	37.55	49.05	41.21	36.77	36.89	45.79	41.42	53.39	36.47
Bases/R ₂ O ₃	1.17	1.00	1.02	0.65	1.49	1.17	1.56	1.46	1.33	1.26	1.33	0.85	1.59
SiO ₂ /R ₂ O ₃	3.23	3.03	3.19	2.64	3.44	3.59	3.45	3.30	3.20	3.64	3.19	2.74	3.32
Hydrolysis	0.37	0.45	0.53	0.71	0.34	0.58	0.36	0.36	0.36	0.50	0.43	0.60	0.35
Calcification	2.46	1.98	1.66	1.35	2.70	1.29	2.54	2.51	2.44	1.70	2.11	1.53	2.60
Salinization	2.95	2.22	2.12	3.35	9.21	0.72	8.29	13.65	12.86	1.68	5.44	8.06	8.16
Product index	76.35	75.21	76.15	72.55	77.46	78.21	77.50	76.76	76.19	78.43	76.13	73.30	76.83

Figure 9. Comparison of Sai red boles and associated basalts with other Deccan bole beds and basalts.

Table 3. Chondrite normalized REE concentrations (ppm) for the bole beds and the associated basalts.

	Profile 1					Profile 2				
	UB1	RB1	RB2	RB3	LB1	UB2	RB4	RB5	RB6	LB2
La	72.4	229.8	254.8	222.4	97.4	78.1	75.96	100.3	158.5	223.6
Ce	57.7	179.1	205.5	179.4	76.3	65.2	55.6	73.48	127.8	189.8
Pr	52.4	136.8	134.5	117.9	61.74	53.75	54.48	71.91	89.76	97.75
Nd	44.36	95.42	86.22	78.83	51.27	42.42	46.29	60.81	64.8	51.08
Sm	35.52	45.52	51.82	48.51	35.78	35.84	30.65	43.7	39.48	32.47
Eu	28.78	36.71	40.16	40.16	27.92	29.3	23.44	40.85	33.09	25.68
Gd	25.94	34.65	43.76	37.49	27.02	25.26	25.89	31.03	31.47	25.8
Tb	24.03	29.37	38.72	32.58	24.3	23.23	23.23	28.84	28.04	21.9
Dy	22.12	22.71	35.58	30.42	21.84	21.33	21.96	27.39	25.38	19.4
Ho	21.69	20.46	33.33	28.04	20.99	20.46	20.81	24.69	23.46	18.17
Er	18.49	17.41	27.95	23.86	17.71	17.41	17.47	22.29	19.88	17.05
Tm	17.57	16.4	26.94	22.26	16.01	16.4	17.18	21.09	19.52	14.45
Yb	18.66	17.5	27.14	22.29	16.9	17.14	17.26	21.2	18.23	14.17
Lu	17.72	18.12	24.81	21.27	15.75	17.72	16.94	19.69	17.72	14.97
LREE	291.3	723.3	773	687.2	350.4	304.6	286.4	391	513.4	620.4
HREE	166.2	176.6	258.2	218.2	160.5	159	160.7	196.2	183.7	145.9
REE	457.5	900	1031	905.4	510.9	463.5	447.2	587.2	697.2	766.3
(La/Yb) _N	3.88	13.12	9.39	9.978	5.76	4.55	4.4	4.73	8.69	15.77
(La/Lu) _N	4.08	12.68	10.27	10.45	6.18	4.4	4.48	5.09	8.94	14.93
(Gd/Yb) _N	1.39	1.97	1.61	1.68	1.59	1.47	1.5	1.46	1.72	1.82
(Eu/Sm) _N	0.81	0.8	0.77	0.82	0.78	0.81	0.76	0.93	0.83	0.79
Ce/Ce*	0.94	1.01	1.11	1.11	0.98	1.01	0.86	0.87	1.07	1.28
Eu/Eu*	0.95	0.92	0.84	0.94	0.9	0.97	0.83	1.11	0.94	0.89

Figure 10. Distribution of rare earth elements in the Sai red boles and associated basalts.

1993; Nesbitt and Markovics 1997; Ma *et al.* 2002). Although, in most cases, weathering results in a relative enrichment of LREEs over HREEs in the weathering profile (Nesbitt 1979; Duddy 1980; Topp *et al.* 1984; Braun *et al.* 1990; Boulange and Colin 1994; Compton *et al.* 2003), the LREEs accumulated during alkaline phases of weathering can be leached out in acidic environment (Ronov *et al.* 1967; Huang and Gong 2001). REE behaviour could trace weathering processes (Gnandi and Tobschall 2003) as weathering induces REE fractionation.

Chondrite normalized REE pattern of both the red boles profiles (table 3) indicate REE fractionation (figure 10a and b) wherein the weathered basalt shows more depletion than the red boles. The distribution pattern of REE, LREE and HREE in both the profiles (figure 10c and d) also indicate rather high depletion of REEs from the basalts, which supports the premise that the red boles escaped further weathering when the associated basalts were undergoing chemical alteration in the Holocene. Eu/Eu^* versus $(\text{Gd}/\text{Yb})_N$ plot (figure 11a and b) suggests that the red boles and associated basalts were affected by intracrustal differentiation as Eu/Eu^* values are more than 0.85.

Also $(\text{Gd}/\text{Yb})_N$ values are less than 2.00, indicating that red boles were not recycled and they are *in-situ* products of basalt weathering.

7. Conclusions

The subaerial 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 sandwiched between the slightly weathered to fresh basalt flows, when compared in terms of the degree of weathering. Therefore, such intrabasaltic palaeosols are being used recently to constrain the palaeoweathering and palaeoclimates during these episodes (Widdowson *et al.* 1997; Hill *et al.* 2000; Sheldon 2002, 2003; Sheldon *et al.* 2002; Solleiro-Rebolledo *et al.* 2003; Tabor *et al.* 2004; Ghosh *et al.* 2006; Sayyed and Hundekari 2006; etc.) as climatic effects of the flood basalts are often considered to be severe. However, a fundamental question is whether such palaeosols can be reliably useful for palaeoenvironmental reconstructions or whether those have been altered by baking or metasomatism (Sheldon 2003). Studies on such palaeosols from different basaltic provinces have so far revealed vital climatic information. The earlier studies on Deccan bole beds suggested that pH during the bole bed formations could have been lower than 6; the weathering conditions were not as intensely oxidizing as in the modern soil formation on basalts (or the modern soils have been forming for much longer) and the absence of pedogenic carbonates in bole beds indicates they formed in a climate with precipitation greater than evaporation (Sayyed and Hundekari 2006). The stable isotopic analyses of clay minerals from bole beds indicate a highly depleted signature of meteoric water providing an evidence of enhanced precipitation or mega monsoonal circulation during the Late Cretaceous period (Ghosh *et al.* 2006). The Sai bole beds also seem to have been formed under similar conditions as seen from physico-chemical and geochemical comparisons as they are not affected much by leaching under present day higher rainfall. These are the signatures of the palaeoweathering conditions of their formation, which have been retained even as the associated basalts show higher intensity of weathering due to the present day higher rainfall. From the present study it is evident that the red bole has retained, to a considerable extent, its original weathering characteristics, as the overlying and underlying basalts have weathered (Holocene weathering) to far more extent indicating the present day weathering conditions. Hence, it can be concluded that the intrabasaltic

Figure 11. $(\text{Gd}/\text{Yb})_N$ versus Eu/Eu^* plot for Sai red boles and the weathered basalt.

palaeosols (bole beds) prove to be of great significance as a palaeoclimatic proxy because post-formational processes like weathering, baking, digenesis, or metasomatism have least affected them as compared to the associated basalts which host them.

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