Article

Inferring palaeoenvironments from geochemical studies of intrabasaltic palaeosols from the Deccan Volcanic Province, India

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Abstract
Three well exposed intrabasaltic palaeosol (bole bed) profiles from the Deccan traps of Ambheri area (Satara district of Maharashtra, India) were studied for their geochemical characteristics to infer the palaeoenvironmental conditions which prevailed during their development. The values of Chemical Index of Alteration (CIA) obtained for the rocks under study suggest that the red boles were formed under incipient to extreme chemical weathering with much more leaching of mobile elements and concomitant enrichment of immobile elements. This is also confirmed by lower values of Parker's Weathering Index (PWI) and Weathering Potential Index (WPI). Mean Annual Precipitation (MAP) and Mean Annual Temperature (MAT) values in general point to moderate rainfall and temperature. The oxic and acidic conditions are inferred from the values of Iron Species Ratio (and Gleization) and Product Index (and Clayeyness). Lower calcination and salinization values suggest semi-humid to humid (also supported by Aridity Index, AI_{koppen}), fairly leached and well drained conditions.

Keywords India; Deccan Volcanic Province; intrabasaltic palaeosols (bole beds); geochemistry; palaeoenvironment.

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1 Introduction

In deducing the palaeoenvironmental conditions during the formation of palaeosols they are compared with their modern analogues in past many years. Besides this important established approach a number of attempts to identify quantitative proxies in palaeosols have gained importance. Such quantitative palaeoenvironmental and palaeoclimatic proxies using the palaeosols mainly include major, trace and rare earth element ratios; geochemical weathering indices; analyses of pedogenic minerals; stable isotopes of palaeosol components; as well as biomarkers like phytoliths, pollen, macro- and micro-fossils. Despite some problems in applying these quantitative approaches such as digenetic alteration due to palaeosol burial, decomposition of soil organic compounds and ambiguity of chemical indices for palaeoenvironmental reconstructions, such proxies have been proved to be of great help in quantifying progressive soil development in soil chronosequences. Ancient intrabasaltic fossil soils (palaeosols) are of great significance in understanding the palaeoenvironments because the chemical alterations of the protolith is a concomitant reactions between the meteoric water equilibrated with the atmospheric gases and the protoliths. In the Indian stratigraphy the Deccan Volcanic Province (Fig. 1) consists of large number of continental flood basalt flows with an estimated volume of more than 1.3 million km^3 (Jay and Widdowson, 2008; Schoene et al., 2015) and originally covering an area of about 1,500,000 km^2 (Krishnan, 1960).The individual lava flows are recognized by physical and chemical breaks indicating quiescence periods i.e. breaks in the volcanic activity.

Today they are seen to be exposed in the regions of western and central peninsular India (in the states of Maharashtra, Madhya Pradesh, Gujarat, Karnataka, Telangana and Andhra Pradesh). The sediments which were deposited during the breaks in the volcanic activity are termed as intertrappean beds while variously coloured intrabasaltic paleosols are supposed to be in-situ weathering products of the underlying parent lava flows. Despite various arguments about their origin the bole beds provide the vital information about the palaeoweathering processes as they represent the weathering regimes in Deccan basalts (Wilkins et al., 1994). Since the weathering profiles, which were formed during the quiescence periods of the volcanic activity, got preserved more easily between successive lava flows they are important continental palaeoweathering records. Hence they can be used in understanding the global palaeoclimates (Widdowson, 1997a, b; Thiry et al., 1999) because they preserve the paleolandscape with strong mineralogical and geochemical fingerprints. In this paper, the intrabasaltic bole beds occurring in the Ambheri area of Satara district of Maharashtra (India) are studied in comparison with the underlying (parent) basalts to infer the palaeoclimatic conditions during their formation.

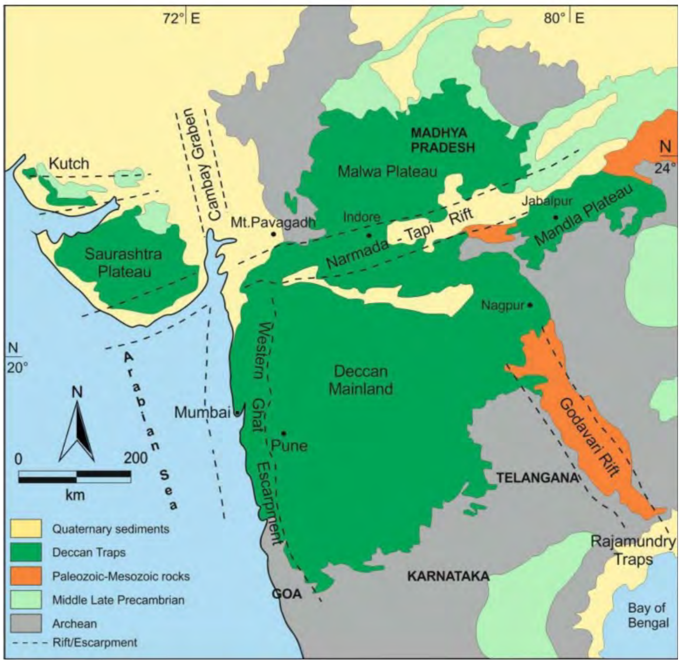

Fig. 1 Geological map of Deccan Volcanic Province of India (after Krishnamurthy, 2020).

2 Intrabasaltic Bole Beds from Deccan Traps

Chenet et al. (2007) termed the Deccan volcanism as pulsed phase eruptions (episodic) characterized by quiescent periods during which the existing lava flows have undergone chemical weathering (Ghosh et al., 2006; Chenet et al., 2008; Srivastava et al., 2012). Such basaltic weathered products were further entombed and preserved by the succeeding lava flow are referred to as "bole beds" (Wilkins et al., 1994; Widdowson et al., 1997; Ghosh et al., 2006; Sayyed and Hundekari, 2006; Shrivastava et al., 2012; Srivastava et al., 2012; Sayyed, 2014, etc.). Bole beds are considered ideal for palaeoenvironmental reconstructions because of their definitive time interval and ease in determining the parent basalt geochemistry (Sayyed, 2014). They are homogeneous, fine-grained clayey material that lack stratification or lamination (Duraiswami et al., 2020) which are few centimeters to a couple of meters thick and can be traced for few meters to many kilometers. The geochemical characterization of bole beds demonstrates that they were formed by the chemical weathering of basalts (Wilkins et al., 1994) with smectites as main constituents (Roy et al., 2001; Ghosh et al., 2006; Greenberger et al., 2012). Duraiswami et al. (2020) proposed yet another mechanism of bole formation i.e. weathering of flow-top and flow-bottom breccias in Continental Flood Basalts (CFB) lava successions which have implications for eruption rates, volcano stratigraphy and other aspects of CFB volcanism. Shukla et al. (2014) on the basis of the mineralogy and geochemistry found that Fe smectite is the predominant clay mineral in the red boles from Deccan Traps which were formed as a result of alteration of underlying basalt flow. Ghosh et al. (2006) on the basis of oxygen isotopic data proposed that at the time of Deccan lava eruption rainfall was significantly high and hence smectite formation of Deccan red bole was much conducive in a temperate-humid climatic condition (Shukla et al., 2014) which allow release of Fe^{2+}, Mg^{2+} and Si^{4+} cations in solutions followed by evaporation leading to super saturation of smectite minerals. Several authors (Ghosh et al., 2006; Sayyed, 2014; Sayyed et al., 2014; etc.) consider that bole beds have undergone pedogenesis and hence they have been referred to as palaeosols which mostly exhibit gradational contact with their parent (underlying) basalt flow which many workers consider as essential criteria to call them as palaeosols (Chenet et al., 2008; Srivastava et al., 2012; etc.). According to Chenet et al. (2008), the presence of red boles from the Deccan Traps of India suggest significant time lapse between the flood basalt flow units.

3 Geology of the Study Area

Satara district of Maharashtra lies on the eastern flanks of the Western Ghats of Indian peninsula and is located about 100 km south of Pune on the Mumbai-Bangalore National Highway No.4. The district is entirely covered by Deccan Trap lava flows of Late Cretaceous to Palaeogene age (68 to 62 Ma) comprising of Aa, Pahoehoe and flows showing mixed characters (GSI, 2001). Lithostratigraphically the lava pile from the district comprises of three formations ranging from lowermost Diveghat Formation and uppermost Mahabaleshwar Formation through Purandargarh Formation of Sahyadri Group. The oldest Diveghat Formation comprises 15 almost aphyric flows showing predominantly mixed characters of Aa and Pahoehoe lava types. Purandargarh Formation comprises of eight basaltic flows that are mostly Aa flows and very few pahoehoe flows. The youngest Mahabaleshwar formation comprises of 9 Aa flows which are mostly phyric in nature. In the areas around Mahabaleshwar, Panchgani and Koyna reservoir tabular masses of lateritic composition occur on the plateau tops having a varying thickness of 15 to 17 meters. In these lateritic masses, at number of places east of Koyna valley, bauxitic material is found in the form of large lenses, pockets or as thin sheets.

4 Methods of the Study

The red bole samples along with their parent lower basalts were collected from the three bole bed profiles occurring around Ambheri area. Using agate mortar and pestle the representative samples were pulverized to fine powder. These crushed and ground samples were then homogenized employing coning and quartering method. Various elements in the samples so prepared were then estimated using AmetekXepos III X-ray fluorescence spectrometer (XRF) at Geology department of Savitribai Phule Pune University (India). FeO concentrations were estimated using volumetric Pratt's method (Saikkonen and Rautiainen, 1993) while H_2O^+ contents were determined by using the methods given by Ball (1964) and Davies (1974).

5 Area of Study and Field Characters of Bole Bed Profiles

During the present study three well exposed red bole profiles occurring in the area of Ambheri (Fig. 2) were systematically sampled along with their parent lower basalts on which these bole beds are developed. These profiles belong to Purandargarh formation of Sahyadri Group of Deccan Traps (Table 1). The field characters including the colour, thickness of the bole beds and their lateral dimensions, contact relationships with the associated basalts and other macro-morphological aspects were noted at each site and are presented in the following sections.

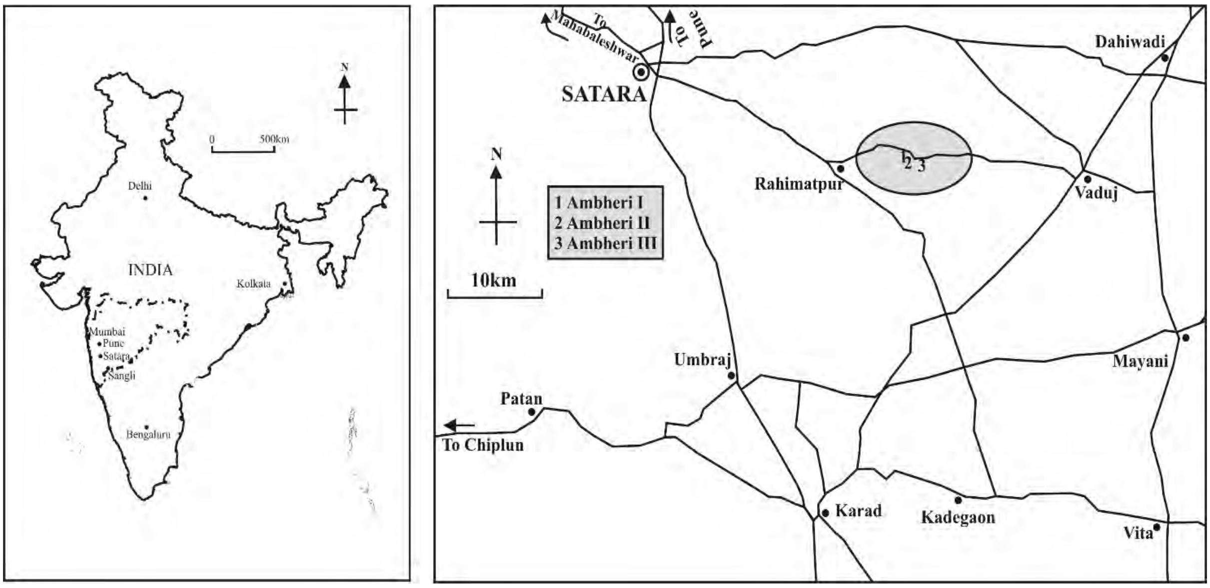

Fig. 2 Location map of the bole bed profiles from the Ambheri area of Satara district (Maharashtra, India).

Table 1 Stratigraphic sequence of the sampling locations of bole beds in the Ambheri area.

Sr. No.	Formation	Sample No.	Location	District	Elevation (meters)
1		C6 (RB)	Ambheri III	Satara	856
2		C4 (RB)	Ambheri II	Satara	808
3	Purandargarh	C2 (RB)	Ambheri I	Satara	794

5.1 Ambheri I Profile

Located at 17°36'17.88"N and 74°16'23.76"E on the right of Vaduj-Rahimatpur road (on the way from Rahimatpur towards Vaduj), the Ambheri I profile exposes a red bole bed having an approximate thickness of 20cm (Fig. 3). The profile belongs to Purandargarh formation of Sahyadri group from the Deccan Traps as sited from the district resource map of Satara (GSI, 2001). The bole bed shows sharp contact with the overlying compact basalt and gradational contact with the very highly weathered underlying zeolitic basalt.

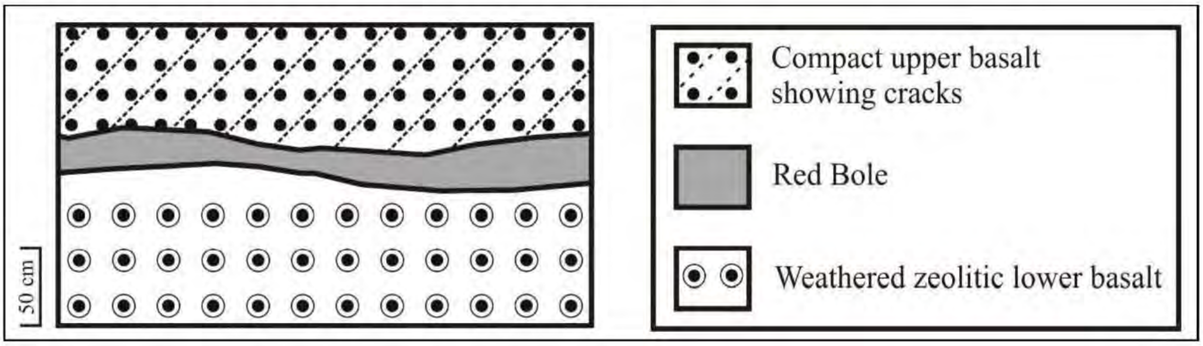

Fig. 3 Lithologic logs of the Ambheri I Profile.

5.2 Ambheri II Profile

Located at 17°36'27.36"N and 74°16'32.40"E on the right of Vaduj-Rahimatpur road (on the way from Rahimatpur towards Vaduj), the Ambheri II profile is found exposing approximately 50cm thick red bole bed (Fig. 4) which is indurated and exhibits pencil joints. The profile belongs to Purandargarh formation of Sahyadri group from the Deccan Traps (GSI, 2001). These red bole also shows sharp contact with the overlying jointed compact and gradational contact with the highly weathered underlying zeolitic basalt.

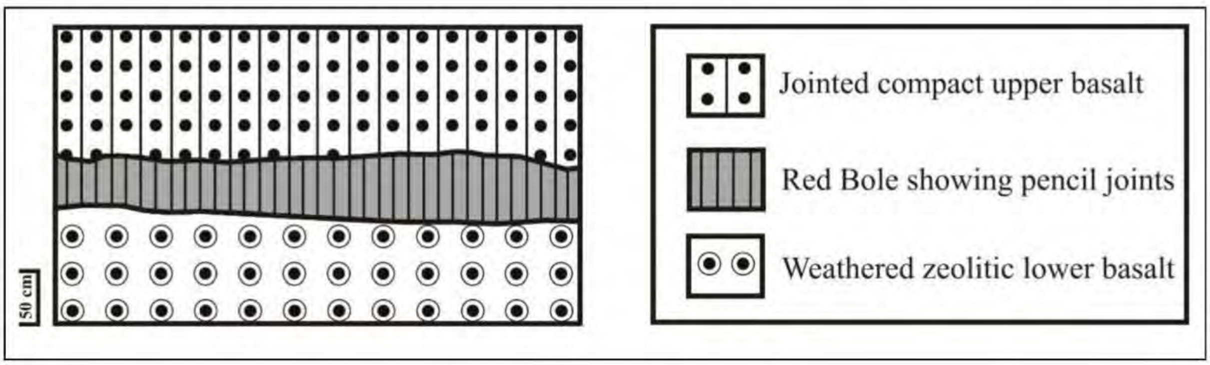

Fig. 4 Lithologic logs of the Ambheri II Profile.

5.3 Ambheri III Profile

Located at 17°36'07.56"N and 74°17'08.58"E on the left of Vaduj-Rahimatpur road (on the way from Rahimatpur towards Vaduj) which exposes a red bole bed having an approximate thickness of 25cm (Fig. 5). The profile belongs to Purandargarh formation of Sahyadri group from the Deccan Traps (GSI, 2001) in which the red bole shows sharp contact with the overlying compact basalt and gradational contact with a very highly weathered underlying basalt.

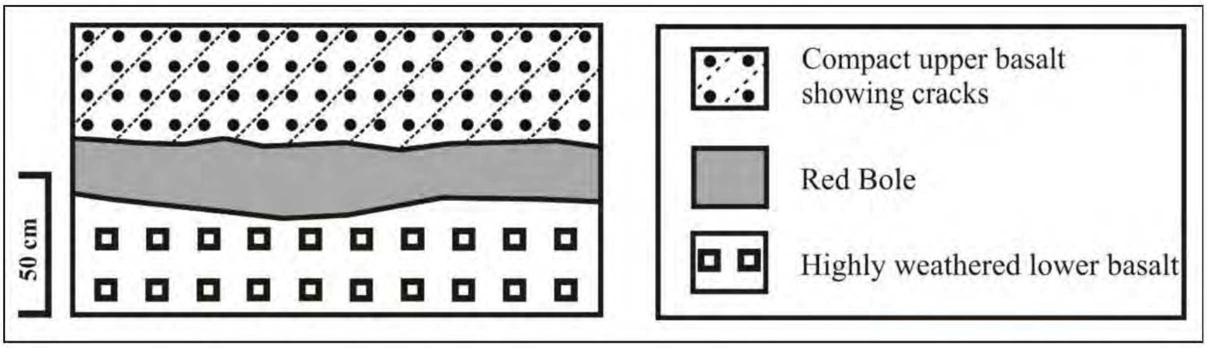

Fig. 5 Lithologic logs of the Ambheri III Profile.

6 Results and Discussion

Using the geochemical data (molecular proportions major element oxides) of the red boles and their underlying parent basalts various geochemical weathering indices were calculated (Table 2). These weathering indices are used in deducing and interpreting the palaeoweathering conditions during the red bole formation.

6.1 Chemical Index of Alteration (CIA)

As per the limits given by Fedo et al. (1995) and Gajere et al. (2015) the CIA values (Fig. 6a) reveals that Ambheri I red bole shows intermediate chemical weathering (CIA=64.7); Ambheri II red bole extreme chemical weathering (CIA=87.2) while Ambheri III red bole is least chemically weathered (CIA=54.4).The CIA values for all the three bole bed suggest removal of mobile cations (Ca^{2+}, Na^{+}, K^{+}) relative to immobile constituent (Al^{3+}) during the chemical alteration which can be attributed to comparatively moderate temperature and varying precipitation conditions during their formation.

6.2 Clayeyness

The values of clayeyness for the red boles (Fig. 6b) are between 0.14 and 0.16 which are more or less similar to their parent basalts (0.15 – 0.19) suggesting notmuch clay mineral formation in the red boles.

6.3 Parker's Weathering Index (PWI)

The lower PWI values (Fig. 6c) for red boles than their parent basalts suggest that red boles are less susceptible to further chemical weathering than their parent basalts. However lower PWI value of parent basalt (PWI=15.0) from Ambheri II suggest that it has been more affected by post bole bed formation chemical weathering.

6.4 Weathering Potential Index (WPI)

WPI values (Fig. 6d) for the Ambheri I and Ambheri III red boles indicate their higher degree of alteration than their parent basalts while Ambheri II red bole seems to have less altered than its parent basalt. This clearly indicates that in the Ambheri II profile the parent basalt shows post bole bed formation weathering.

6.5 Product Index (PI)

PI values for the bole beds from all the three profiles (Fig. 6e) suggest relative increase in the silica content in them as compared to their respective lower basalts. This suggests that the weathering conditions were not favourable for leaching of silica during bole bed formation and hence point towards rather acidic conditions.

6.6 Iron Species Ratio (ISR)

The high Iron Species Ratios (7.62 to 94.17) in bole beds (Fig. 6f) as compared to their parent basalts from all the three profiles suggest oxidizing conditions which was prevalent during red bole formation.

6.7 Gleization

Quite low gleization values (Fig.7a) for all the three red boles (0.01 to 0.13) suggest their formation under oxidizing and well drained conditions.

6.8 Mean Annual Precipitation (MAP)

The MAP values obtained for all the three red boles (Fig.7b), although showing much variations (668mm - 1242mm)suggest their formation under moderate rainfall (i.e. the conditions were not much wet).

6.9 Mean Annual Temperature (MAT)

The MAT values for all the three red boles (Fig.7c) are more or less similar (between 15.9^{o}C and 17.1^{o}C) suggesting moderate temperature (not much warm) conditions during their formation.

6.10 Hydrolysis

The hydrolysis values for the red boles (Fig. 7d) from Ambheri I and Ambheri III are considerably similar suggesting the leaching was not much as compared to Ambheri II red bole which can be related to the fact that the conditions during their formation were not much wet and less warmer which is also evident from the MAP and MAT values.

6.11 Calcination

Lower calcination values (Fig. 7e) for the red boles (which is quite less in Ambheri II red bole indicate that there was considerable leaching of alkaline earth elements implying humid conditions during their formation.

6.12 Salinization

Very low values of salinization (0.01 to 0.08; well below the threshold value of 1) for all the red boles (Fig. 7f) suggest their formation under well drained conditions resulting in the removal of the mobile alkali elements (Na^+ and K^+).

6.13 Aridity index

The values of aridity index ($AI_{\text{Köppen}}$) suggest that all the three red boles were formed under semi-humid to humid conditions (Fig. 8).

Table 2 Geochemical weathering indices for the rocks from Ambheri area.

Profile Name	**Ambheri I**		**Ambheri II**		**Ambheri III**	
Elevation (m)	**794 m**		**808 m**		**856 m**	
Sample No.	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Sample Type	**Lower Basalt**	**Red Bole**	**Lower Basalt**	**Red Bole**	**Lower Basalt**	**Red Bole**
Chemical Index of Alteration (Nesbitt and Young, 1982)	40.19	64.70	70.49	87.19	36.38	54.38
Clayeyness (Sheldon and Tabor, 2009)	0.15	0.15	0.19	0.16	0.15	0.14
Parker's Weathering Index (Parker, 1970)	44.31	28.37	15.04	13.41	50.16	31.91
Weathering Potential Index (Reiche, 1943)	-3.84	-20.13	-32.64	-1.73	5.11	-4.10
Product Index (Reiche, 1943 and 1950)	73.27	75.82	71.24	74.57	74.87	76.37
Iron Species Ratio (Holland, 1984)	2.59	94.17	19.88	54.80	3.93	7.62
Gleization (Retallack, 2001)	--	0.01	--	0.02	--	0.13
Mean Annual Precipitation (Sheldon et al., 2002)	--	818.16	--	1241.72	--	667.50
Mean Annual Temperature (Sheldon et al., 2002)	--	16.01	--	17.09	--	15.91
Hydrolysis (Retallack, 2001)	--	0.56	--	1.26	--	0.50
Calcination (Retallack, 2007)	--	1.71	--	0.78	--	1.92
Salinization (Retallack, 2001)	--	0.07	--	0.01	--	0.08
Aridity Index (AI_{Koppean}) (Köppen, 1923)	--	16.7	--	24.8	--	13.6

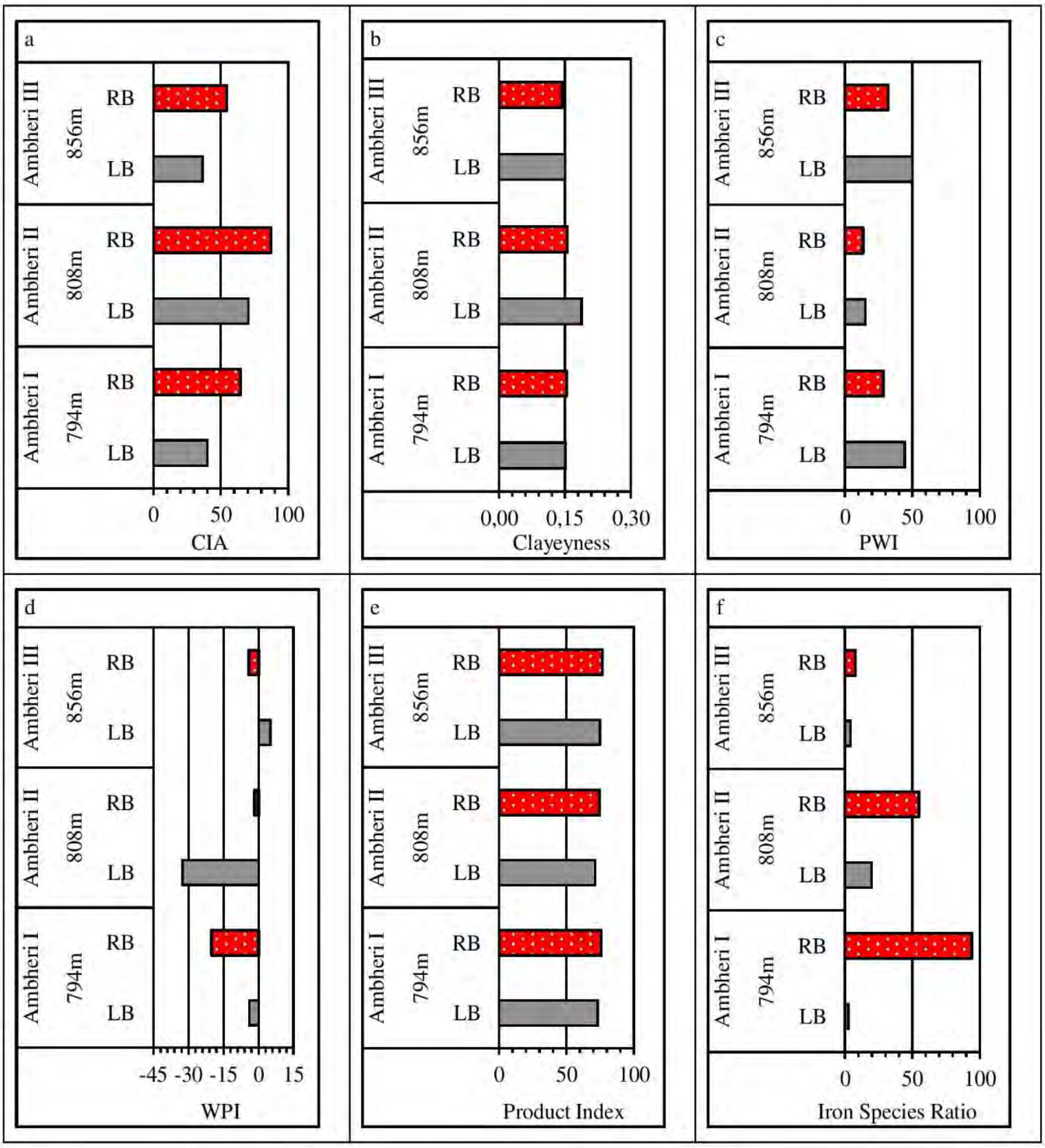

Fig. 6 Variations in the values of chemical weathering indices for the rocks from Ambheri area.

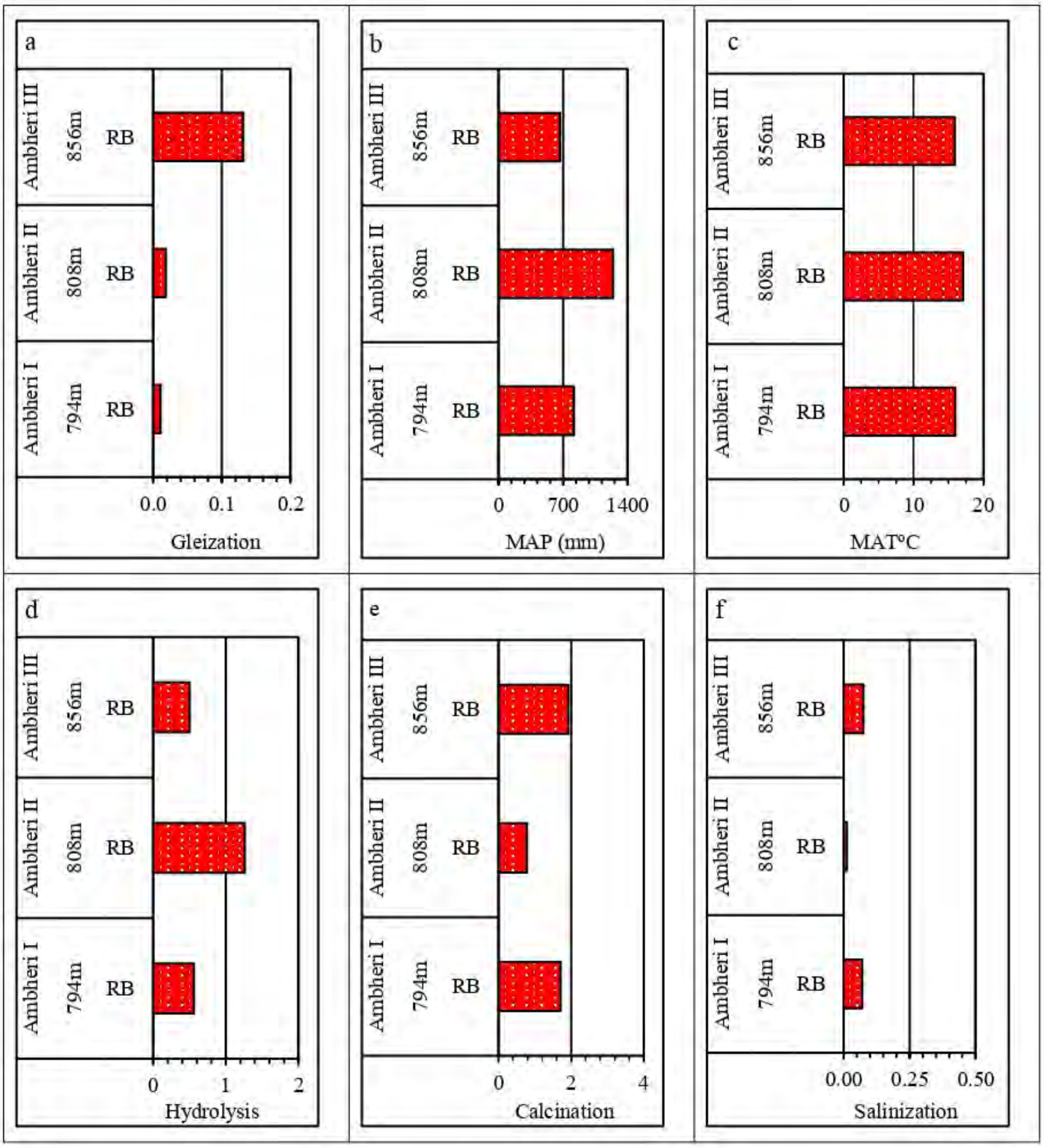

Fig. 7 Variations in the values of chemical weathering indices for the rocks from Ambheri area.

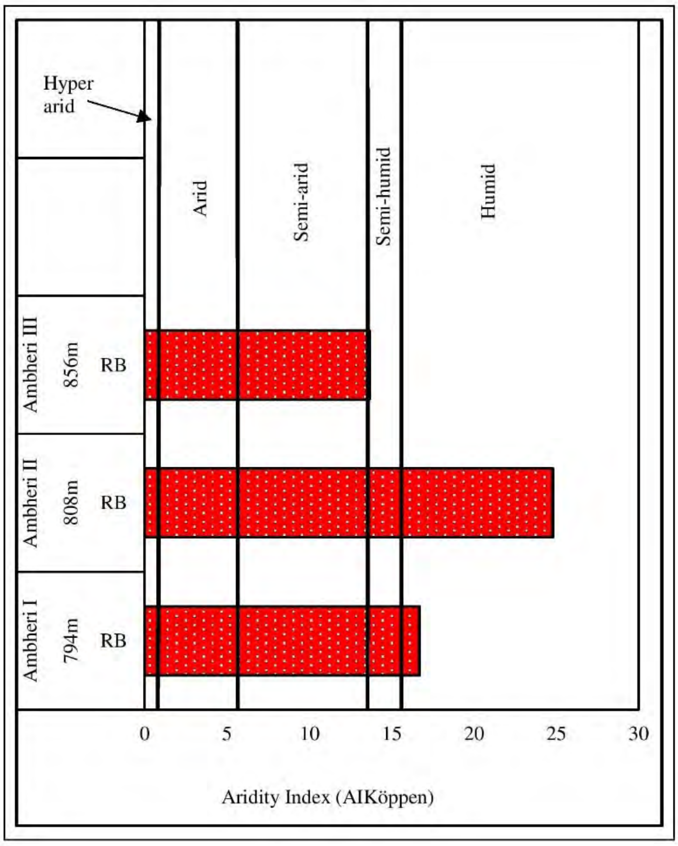

Fig. 8 Variations in the Aridity Index ($AI_{Köppen}$) for the red boles from Ambheri area.

7 Conclusions

The following palaeoweathering and palaeoenvironmental conditions are inferred which prevailed during the formation of red bole bedsusing various chemical weathering indices.

1. The red boles from Ambheri area were formed under moderate to extreme chemical weathering without much clay mineral formation.
2. As compared to their parent basalts the red boles in general show higher degree of chemical weathering thereby suggesting their less susceptibility to further chemical alteration.
3. All the red boles were formed under quite oxidizing, well drained and rather acidic environment.
4. The MAP and MAT values suggest their formation under conditions which were neither much wet nor much warm.
5. In general the red boles show considerable leaching of mobile cations (alkali and alkaline earth elements) suggesting semi-humid to humid and well drained conditions.

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