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Mineralogy and geochemistry of various colored boles from the Deccan volcanic province: Implications for paleoweathering and paleoenvironmental conditions

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ABSTRACT

Boles are markers of hiatus in successive eruptions of the Deccan flood volcanism (DFV) emplaced at the Cretaceous-Paleogene boundary that are interpreted to retain paleoenvironmental information from their subaerial exposure. To evaluate paleoenvironment during these hiatuses, mineralogy and geochemistry of three different colors of boles, i.e., red (dark = 10R-3/6 and light = 10R-4/8), brown (5YR-4/4) and green (5G-6/2) were examined. The plagioclase index of alteration (PIA) (loss of Ca and Na relative to Al) was between 76 and 81 for all the boles, indicating moderate chemical weathering that is probably due to their short subaerial exposures. Mass balance calculations show significant enrichments of K, Si, Mg and Rb in green and brown boles suggesting an allochthonous input that is interpreted as volcanic ash fallout. Mineralogically, the red bole is dominated by montmorillonite and hematite, the brown bole of ferruginous smectite and montmorillonite, and the green bole of celadonite and nontronite.

Montmorillonite and hematite genesis in red boles indicates leaching in an oxidative environment at near neutral pH (~5.5 to 8) conditions. Further, heating of the altered basalt from emplacement of upper lava flows under subaerial-dry conditions could have also promoted the formation of hematite in red boles. The hydrothermal alteration of K and Mg enriched volcanic ash admixed with the altered lower flow basalt under slightly reducing oxidation potential led to the genesis of nontronite and celadonite in the green bole. The aluminous Fe-smectite in brown bole occurred from hydrothermal alteration of aluminous clays (e.g., montmorillonite). The different colored boles, therefore, suggest a range of weathering processes including chemical leaching to hydrothermal alteration in oxidative to reducing environmental conditions throughout DFV emplacement that could reflect changing surficial conditions associated with volcanically forced changes to the environment.

1. Introduction

The Deccan Traps is the most recent and one of the largest continental flood basalt provinces, presently covering an area of ~500,000 km^2 in central and western India (Jay and Widdowson, 2008). Recent geochronological studies of Deccan lava flows suggest a significant contribution of Deccan flood volcanism (DFV) to the Cretaceous-Paleogene boundary (KPB) mass extinction (Renne et al., 2015; Schoene et al., 2015). The inter-flow boles, widely interpreted as paleoweathering surfaces, are markers of quiescence during DFV (Chenet et al., 2008; Ghosh et al., 2006; Renne et al., 2015; Srivastava et al., 2012, 2015; Widdowson et al., 1997). As such, boles have potential to provide significant information on paleoenvironmental conditions (Ghosh et al., 2006; Srivastava et al., 2012, 2015). Recent studies have also suggested boles as possible analogs of Martian phyllosilicates (Craig et al., 2017; Greenberger et al., 2012).

Boles are weathering products of basalts that are variably admixed with volcanic ash and through their description, chemistry, mineralogy, and magnetic properties have been used to derive information related to subaerial alteration (Ghosh et al., 2006; Sayyed and Hundekari, 2006; Srivastava et al., 2012, 2015, 2016; Wilkins et al., 1994; Widdowson et al., 1997; Walker, 1999). Boles occur in the form of strata, lensoid shapes, and as pocket fillings with varied thickness (~0.10 to 1 m) in the Deccan Traps (Chenet et al., 2008; Srivastava et al., 2012; Walker, 1999) with several different colors (e.g., red, yellow, brown and green). The occurrence of red boles is the most common, whereas green boles are rare (Ghosh et al., 2006; Srivastava et al., 2012).

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Only a limited number of studies have been carried out on a single representative sample of boles in the Deccan Traps to understand their mineralogical and geochemical properties (Chenet et al., 2008; Craig et al., 2017; Ghosh et al., 2006; Sayyed et al., 2014; Shrivastava et al., 2012; Widdowson et al., 1997). Further, only a few studies have focused on depth wise variations in the geochemical properties of red boles relative to their parent basalt (Inamdar and Kumar, 1994; Sayyed et al., 2014; Wilkins et al., 1994). The rare occurrence of green boles as a complete weathering profile has also limited the studies to isolated patches present within red boles and/or as infillings (Ghosh et al., 2006; Srivastava et al., 2012). The different colors of bole have been attributed to distinct mineralogical compositions, e.g., hematite in red boles, and celadonite and nontronite in green boles (Craig et al., 2017; Walker, 1999; Srivastava et al., 2015), and recently, Craig et al. (2017) suggested that these different mineralogical compositions represent distinct patterns of magnitude of alteration. However, further study on the mineralogical composition of different colored boles in corroboration with geochemical information, and on boles from different locations, are required to develop a better understanding on paleoweathering and paleoenvironment during DFV. Therefore, four well-developed bole profiles of three different colors i.e., red [dark red (Munsell notation = 10R-3/6) and light red (Munsell notation = 10R-4/8)], brown (Munsell notation = 5YR-4/4) and green (Munsell notation = 5G-6/2) with thicknesses varying between ~68 and 130 cm from the Pune, Satara and Ahmednagar districts of Maharashtra were sampled to cover multiple depths at each location. Petrography, X-ray diffraction (XRD), Fourier transform infrared (FTIR) spectroscopy, and X-ray fluorescence (XRF) analyses were conducted to understand mineralogical and geochemical changes in different colored boles and host basalts.

2. Study area

The occurrences of boles in the Deccan Traps have been reported from many localities in Maharashtra, Madhya Pradesh and Gujarat (Ghosh et al., 2006; Inamdar and Kumar, 1994; Srivastava et al., 2012, 2016; Widdowson et al., 1997). Chemostratigraphically, the boles are frequent in the Wai Subgroup and uncommon in the Lonavala and Kalsubai Subgroups (Renne et al., 2015; Widdowson et al., 1997). The area in and around Pune and Ahmednagar districts of Maharashtra shows a high frequency of bole occurrences (Fig. 1).

The brown (DG-2-BB) and dark red bole (DG-3-RB) profiles are located in the Dive Ghat section in the Pune district (Fig. 2b and c) at elevations of ~806 and 744 m a.s.l., respectively, and are chemostratigraphically classified in the Poladpur formation of the Wai Subgroup (Duraiswami et al., 2008). Craig et al. (2017) and Ghosh et al. (2006) studied mineralogical and geochemical properties on a single representative sample from the red bole profile. Srivastava et al. (2012, 2015) reported mineral magnetic properties of the DG-2-BB and DG-3-RB profiles. The brown bole shows a sharp contact with the upper, unaltered rubbly pahoehoe lava flow and a gradational contact with relatively altered lower lava flow. The brown bole shows a maximum thickness of ~130 cm in the central part with varying thickness over lateral extent of ~10–15 m. The brown bole is friable and contains bedding features like lamination and fissility (Srivastava et al., 2012). The ~80 cm thick dark red bole profile shows a sharp contact with the upper lava flow. The hardened clay in the dark red bole is due to higher compaction (Ghosh et al., 2006), and/or heating from the upper lava flow (Srivastava et al., 2012).

The light red (SBH-RB) bole profile is exposed in a quarry section (~634 m a.s.l.) at the Satara-Bengaluru highway (NH48), Satara district. The light red bole (~70 cm thick) has a sharp upper and gradational lower contacts with adjacent lava flows. The upper lava flow of SBH-RB profile shows typical spheroidal weathering (Fig. 2d). In an extensive field survey of the western - Deccan volcanic province (DVP), we encountered a ~68 cm thick green color bole in a quarry section (~601 m a.s.l.) near Wadgaon village, Ahmednagar district (Fig. 2a). It has ~20 m of lateral exposure with varying thickness throughout the profile. The green (A-GB) bole profile selected from this exposure shows a sharp contact with the upper rubbly pahoehoe lava flow. The upper flow basalt overlying this green bole profile shows well-developed red color (iron oxide) weathering rinds (Fig. 2a inset). The green and brown bole profiles show a ~2 to 5 cm thick reactive surface at the contact with the upper lava flow. The term reactive surface is used here for the hydrothermally altered sole of the upper lava flow, which has formed from its own last liquid water fraction (Chenet et al., 2008) and/or upon contact with the underlying hydrous substrate (hydrous bole) (Srivastava et al., 2012). Chemostratigraphically, the host basalts of the light red and green boles also fall in the Poladpur formation of the Wai Subgroup.

2.1. Sample collection

Twenty samples from the four profiles, including basalts from the over- and underlying flows and the reactive surfaces, were collected. The lower flow basalt from each respective bole profile is considered as the parent rock to assess relative chemical changes in the bole. We did not find any prominent pedogenic features, such as plant fossils and/or presence of organic matter, in the boles. The boles represent a single unit or strata in the field and do not show any distinguishing features throughout the profiles; therefore, we collected bole samples as upper, middle and/or lower boles to understand depth wise geochemical variations during paleoweathering.

3. Laboratory methods

3.1. Sample preparation

Whole-rock samples of basalts, boles, and reactive surfaces were powdered to −200 mesh size for X-ray diffraction, Fourier transform infrared spectroscopy, X-ray fluorescence and loss on ignition (LOI) analyses.

3.1.1. Clay separation

Clay fractions from bulk samples of each bole were separated for the clay mineral characterization. The bulk samples were first disaggregated in distilled water and transferred to 1000 mL cylindrical beakers. Each sample was treated with 1 N HCl, followed by H_2O_2 to dissolve any carbonate and organic matter present. The sodium hexametaphosphate [$(NaPO_3)_6$] was added to samples as the deflocculant. The samples were then sonicated and allowed to settle for ~1 h. The top 200 mL of suspended solution from each sample was collected through a micropipette and the $< 2.0\ \mu m$ particle-size fraction was separated by centrifuge settling. The clays were then air-dried for XRD and FTIR analyses. The clays were also glycolated at 60 °C overnight for XRD analysis (Borrelli et al., 2014; Moore and Reynolds, 1997).

3.1.2. Petrography

Thin sections of the upper and lower flow basalts were prepared at the Department of Geology, Savitribai Phule Pune University (SPPU). Thin sections were studied using an upright Nikon advanced microscope and the NIS-Elements BR 3.2 software was used for the photomicrographs.

3.2. Analytical techniques

3.2.1. X-ray diffraction

The XRD analysis of basalts, boles (bulk and clay), and reactive surfaces was carried out at the Advanced Instrumentation Research Facility (AIRF), Jawaharlal Nehru University (JNU). The XRD scans were collected on a PANalytical 'X'Pert Pro-MPD X-ray Diffractometer. The scans were run using a CuK_{α} anode with a voltage of 45 kV and