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Geochemical Evidences for Possible Absence of Cu-Sulfide Deposits in the Deccan Volcanic Province, India

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ABSTRACT

Continental flood basalt provinces (CFBs) are important hosts for large-scale Cu-sulfide deposits. However, sulfide mineralization is yet to be discovered, if any, in the end-Cretaceous Deccan volcanic province, India. In the present study, geochemical evidences for the possible absence of Cu-sulfide deposits associated with the Deccan basalts by analyzing and comparing the geochemistries of the Deccan and Siberian CFBs are provided. The Fe-rich nature and high fO_2 conditions did not favour sulfide saturation at any stage of magma evolution in the Deccan province. Crustal contamination of the Deccan magmas also did not increase the sulfur budget. The most contaminated basalts of Bushe and Poladpur formations of the Deccan province do not show any depletion in the copper contents compared to other formations. In the absence of sulfide saturation, copper behaved as an incompatible element in the Deccan magmas in contrast to the Siberian basalts, in which copper behaved as a compatible element during magma evolution due to sulfide saturation consequently formed world-class copper sulfide deposits. It is demonstrated that the lithosphere- and asthenosphere-derived Deccan magmas have similar Cu abundances thereby suggesting that the Cu-sulfide deposits associated with the CFBs are process-controlled rather than source-controlled. Although Cu-sulfide deposits may not have formed, the geochemical patterns suggest favourable conditions for native copper mineralization in the Deccan volcanic province. In the present study, a set of geochemical proxies that can be utilized as preliminary exploration tools for Cu-sulfide mineralization in the CFBs is proposed.

INTRODUCTION

Copper sulfide ore formation in continental flood basalts (CFBs) is a much-debated topic in the realm of magmatic ore deposits. Some of the CFBs designated as "fertile provinces" are hosts to large-scale Cu, Ni and PGE sulfide deposits (for example Siberia, Emeishan, Tarim, Karoo provinces; Zhang et al., 2008); however, some other CFBs designated as "barren provinces" are devoid of sulfide deposits (for example Deccan, Parana, Ferrar provinces; Zhang et al., 2008). Zhang et al. (2008) and Griffin et al. (2013) argued that the ancient cratonic lithospheres contributed substantially to the budget of Cu and Ni to the plume magmas, which eventually formed large sulfide deposits associated with the fertile CFBs; whereas in the barren CFBs, sub-continental lithosphere contribution was minimal. Alternately, Lee et al. (2012) suggested that copper abundances are not distinctly different in the plume-, arc- and ridge-derived primary basaltic magmas consequently inferred that the ore deposit formation is linked to magma evolution process rather than mantle source and primary melt compositions.

In either case (*source-controlled* or *process-controlled*), ultimate formation of the sulfide deposit requires concentration of the ore and its separation from the silicate fraction. Factors that influence sulfur-saturation of the magma and physical segregation of sulfide minerals include (1) degree of mantle melting, (2) FeO, SiO_2 and Na_2O+K_2O contents in the magma, (3) fO_2 and fS_2 fugacities, (4) P-T conditions, (5) assimilation of crustal sulfur and (6) liquid immiscibility. Moderate degrees of mantle melting (~ 20%) produce highest amount of sulfur in the melt (Keays, 1995; Arndt et al., 2005). At lower degrees of melting sulfide phase would be in mantle residue and higher degrees of melting results in the dilution of sulfur in the melt (Wendlandt, 1982; Keays, 1995; Rehkämper et al., 1999). Lower concentration of FeO, high concentrations of SiO_2, $Na_2O + K_2O$ are favourable for sulfide ore formation (MacLean, 1969; Haughton and Roeder, 1974; Buchanan and Nolan, 1979; Naldrett, 2004). Sulfur content needed for sulfide saturation increases exponentially with fO_2 (Jugo et al., 2005; Jugo, 2009). It was estimated that 1300 ppm S is sufficient to induce sulfide saturation at FMQ-1 and 1500 ppm at FMQ+1 for MORB; 7500 ppm at FMQ+2 for back-arc and ocean island basalts and can be as high as 1.4 wt.% at FMQ+2.3 for island-arc basalts (Jugo, 2009). At FMQ+2 conditions, most of the sulfur occurs in sulfate state which has 10 times higher solubility than sulfide (Carroll and Rutherford, 1987; Jugo et al., 2005; Mungall et al., 2006; Jugo, 2009). High temperature magmas dissolve higher amounts of sulfur (Naldrett, 2004; Barnes and Lightfoot, 2005) whereas decreasing pressure increases S solubility in the magma (Mavrogenes and O'Neil, 1999). Therefore, rapid adiabatic ascent of the magma would shift the magmas into the field of sulfur undersaturation (Mavrogenes and O'Neill, 1999) thereby inhibits sulfide ore formation. Crustal contamination is a key process which brings S-undersaturated tholeiitic basaltic magmas to S-saturation and subsequent sulfide ore formation (Brugmann et al., 1993; Wooden et al., 1993; Lightfoot et al., 1990, 1993 and 1994; Hawkesworth et al., 1995; Naldrett et al., 1992, 1995; Lightfoot and Keays, 2005). Assimilation of crustal material is a crucial factor in sulfide saturation because it will influence temperature, SiO_2, Na_2O+K_2O and also adds sulfur to the magma. Solubility of sulfide in mafic-ultramafic magmas decreases with increasing $a\mathrm{SiO_2}$ and $a\mathrm{Na_2O}$ (MacLean, 1969). Addition of sulfur from the crustal sources to the mantle-derived magmas aids to raise sulfur saturation to the levels at which sulfide segregates (Naldrett, 1999; Naldrett et al., 1992; Lesher and Campbell, 1993; Ripley et al., 2002; Arndt et al., 2005; Lightfoot and Keays, 2005; Wilson and Churnett, 2006). The relationship between assimilation of crustal sulfur by parental magmas and segregation of magmatic sulfides is well recognized in Noril'sk-Talnakh, Voisey's bay and Tarim Basin (Naldrett, 1999).

One geochemical feature that is firmly established in the CFBs is chalcophile element (Cu, Ni, PGE) depletion in silicate magmas (basalts) associated with sulfide ores (Brugmann et al., 1993; Czamankse et al., 1994; Fedorenko, 1994; Lightfoot et al., 1994; Lightfoot and Keays, 2005). The erupted basalts, equilibrated with sulfide ore, are supposed to show chalcophile depletion whether sulfide saturation took place in large deep magma chambers (Brugmann et al., 1993), in narrow shallow magma chambers (Rad'ko, 1991; Naldrett

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