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Density, Viscosity and Velocity (Ascent Rate) of Alkaline Magmas

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ABSTRACT

Three distinct alkaline magmas, represented by shonkinite, lamprophyre and alkali basalt dykes, characterize a significant magmatic expression of rift-related mantle-derived igneous activity in the Mesoproterozoic Prakasam Alkaline Province, SE India. In the present study we have estimated emplacement *velocities (ascent rates)* for these three varied alkaline magmas and compared with other silicate magmas to explore composition control on the ascent rates. The alkaline dykes have variable widths and lengths with none of the dykes wider than 1 m. The shonkinites are fine- to medium-grained rocks with clinopyroxene, phologopite, amphibole, K-feldspar perthite and nepheline as essential minerals. They exhibit equigranular hypidiomorphic to foliated textures. Lamprophyres and alkali basalts characteristically show porphyritic textures. Olivine, clinopyroxene, amphibole and biotite are distinct phenocrysts in lamprophyres whereas olivine, clinopyroxene and plagioclase form the phenocrystic mineralogy in the alkali basalts. The calculated densities [2.54-2.71 g/cc for shonkinite; 2.61-2.78 g/cc for lamprophyre; 2.66-2.74 g/cc for alkali basalt] and viscosities [3.11-3.39 Pa s for shonkinite; 3.01-3.28 Pa s for lamprophyre; 2.72-3.09 Pa s for alkali basalt] are utilized to compute velocities (ascent rates) of the three alkaline magmas. Since the lamprophyres and alkali basalts are crystal-laden, we have also calculated effective viscosities to infer crystal control on the velocities. Twenty percent of crystals in the magma increase the viscosity by 2.7 times consequently decrease ascent rate by 2.7 times compared to the crystal-free magmas. The computed *ascent rates* range from 0.11-2.13 m/sec, 0.23-2.77 m/sec and 1.16-2.89 m/sec for shonkinite, lamprophyre and alkali basalt magmas respectively. Ascent rates increase with the width of the dykes and density difference, and decrease with magma viscosity and proportion of crystals. If a constant width of 1 m is assumed in the magma-filled dyke propagation model, then the sequence of emplacement velocities in the decreasing order is alkaline magmas (4.68-15.31 m/sec) > ultramafic-mafic magmas (3.81-4.30 m/sec) > intermediate-felsic magmas (1.76-2.56 m/sec). We propose that SiO_2 content in the terrestrial magmas can be modeled as a semi-quantitative "geospeedometer" of the magma ascent rates.

INTRODUCTION

The main mechanism of migration of magmas through lithospheric mantle and crust is by propagation of magma-filled cracks i.e. dykes (Shaw, 1980; Spera, 1984; Russell et al., 2012). Dykes allow rapid transport of magma without large scale crystallization *en route*; as a result they represent connecters between regions of melt production and regions of magma accumulation/eruptions. The dykes inject either through pre-existing fractures or create their own pathways by hydraulic fracturing involving dilation of the country rocks. In the field, it is generally observed that fractures do not continue beyond the terminus of the dyke suggesting that magma itself opens fractures to form dykes (see Wada, 1994).

Magma pressure and regional stress field in addition to the host-rock characteristics are the dominant factors that control the length/width ratios, change in orientation, and growth of dykes (Pollard and Muller, 1976). With increasing depth the attitude of the dykes become relatively uniform, but at shallow levels their orientations are controlled by local planes of weakness consequently more irregular dyke patterns are produced. However, different magmas with constant magma pressure emplacing into the same host rocks under similar regional stress conditions show differences in the length/width ratios and thicknesses, suggesting that magma composition also plays a role in the dyke emplacement and growth patterns (Halls and Fahrig, 1987; Ernst et al., 1995). Since viscosity and density of the magmas are controlled by volatiles in addition to the major element chemistry, the emplacement styles of dry and wet magmas with the same bulk-rock compositions are also expected to be different as established by field observation, experiment and theoretical modeling (Pollard et al., 1982; Rogers and Bird, 1987; Olson and Pollard, 1989; Thomas and Pollard, 1993).

Dyke width (a simple measurable quantity in the field) is a significant parameter in understanding and evaluating magma emplacement mechanisms. Magmatic pressure, viscosity, compressive stress acting on dyke plane and elasticity of the host-rock control the width of the dykes and ascent rate of magmas (Pollard, 1987). Dyke width is positively correlated with SiO_2 content and K_2O/MgO ratios (Ui et al., 1984; Wada, 1994). A positive correlation between dyke width and viscosity is also suggested by Wada (1994) thereby implying that felsic dykes would be broader than mafic dykes. However, large mafic dykes (widths >100 m) observed in the Archaean/Proterozoic terrains and Phanerozoic flood basaltic provinces could be due to anomalously high magmatic temperatures related to hotspot activities or any local anomalous thermal conditions (Wada, 1994).

Magma migration in the mantle and crust is essentially buoyancy-driven (Lister and Kerr, 1991). The magma ascent rate is controlled by density difference between magma and ambient crust, speed of crack propagation, and viscosity of the magma (Dingwell and Webb, 1990; Melnik and Sparks, 2005; Whittington et al., 2009). While density difference reflects the scale of buoyancy, volatiles have direct bearing on the crack propagation speed and viscosity of the magma. Magma ascent rates for silicate magmas, which are in the order of < mm/sec to > m/sec, are estimated by using a variety of methods including fluid-filled propagation model, element diffusion profiles in minerals, thickness of mineral growth rims, xenolith settling velocity, dP/dT and dT/dt variation, high-PT experiments and numerical modeling (Spera, 1984; Klügel et al., 1997, Nicholis and Rutherford, 2004; Demouchy et al., 2006; Peslier and Luhr, 2006; Sparks et al., 2006; Mattsson, 2012; Yamato et al., 2012; Armienti et al., 2013; Baruah et al., 2013; Jankovics et al., 2015; Ray et al., 2016). Among the different methods used for calculating magma propagation velocities, it is found that fluid-filled crack propagation model seems to estimate higher ascent rates (Jankovics et al., 2015; Ray et al., 2016).

In the present study an attempt has been made to quantify the

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