New thermobarometers for martian igneous rocks, and some implications for secular cooling on Mars

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ABSTRACT

Tests show that terrestrial mineral+liquid geothermobarometers are not well equipped for use on martian rocks, which tend to have much higher FeO and lower Al2O3. Here, we present new calibrations of thermometers and barometers using experimental data on martian samples from the literature. These new models recover P-T conditions with a greater accuracy compared to models calibrated using terrestrial compositions. We applied these new calibrations to primitive martian mantle-derived melts Yamato 980459 (Y98) and Northwest Africa (NWA) 6234 and several surface basalts (Gusev). Our new models yield similar P-T conditions for NWA and Y98 compositions of 1.4–1.7 GPa and 1500–1550 °C, which are close to estimates by most prior studies. Our models yield somewhat lower P estimates compared to Lee et al. (2009), apparently because our Si-activity model (from Beattie 1993) includes an Al2O3-correction (where lower Al2O3, as in martian samples, leads to lower P estimates). For Gusev basalt compositions, our new models yield P-T estimates of 1.0–1.3 GPa and 1340–1390 °C; furthermore, we also obtain P = 1.03 GPa and T = 1340 °C, for a Gusev composition from Monders et al. (2007), which comes very close to the Monders et al. (2007) estimate for multiple saturation, of 1.0 GPa and 1325 °C, derived from phase saturation relationships. Given the different ages of these meteorites, with Gusev at 3.65 Ga (Greeley et al. 2005) and Y98 at 4.3 Ga (Bouvier et al. 2005, 2008, 2009; Werner et al. 2014), their thermal contrasts may represent secular cooling of Mars. We estimate a mantle potential temperature difference of ~200 °C, with mantle potential temperatures of 1450 ±50 °C for Gusev and 1650 ±50 °C for Y98; this implies a cooling rate of 300 °C/Ga. This would appear to be a much more rapid rate of cooling compared to Earth, as may be expected by Mars’ higher surface/volume ratio.

Keywords: Geothermobarometry, thermobarometry, martian meteorites, experimental petrology, martian geology, thermometer, barometer, Mars, petrology, SNC meteorites

INTRODUCTION

Geothermobarometers are useful tools as they lend insights into the inner workings of planetary bodies (see Essene 1989; Brey and Köhler 1990; Putirka et al. 1996; Putirka 2008). This was illustrated during the Apollo era, when return samples from the Moon gave scientists unique opportunities to apply geothermobarometry to a planetary body other than Earth (see McCallum and Schwartz 2001; Lee et al. 2009). For example, workers discerned lower to middle crustal depths of recrystallization and partial melting in lunar samples (McCallum and Schwartz 2001), which bolstered arguments for convective overturn of the lunar mantle early in its history (Lee et al. 2009). However, as indicated by Filiberto and Dasgupta (2011) and as we show below, thermobarometers calibrated on terrestrial compositions (Putirka et al. 1996; Putirka 2008) are poor predictors of P and T when applied to experiments performed on martian bulk compositions. We thus calibrate new thermometers and barometers that are specific to martian bulk compositions.

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Martian meteorites

Martian meteorites are primarily comprised of basalts and basaltic cumulates (Shergottites), Ca-rich clinopyroxene cumulates (Nakhlites), and Dunites (Chassignites) in addition to other unique samples such as orthopyroxenite ALH84001 (Papike et al. 2009) and a porphyritic basaltic monomict breccia NWA7034 (Agee et al. 2013). Shergottites themselves are typically further subdivided into basaltic, ilherzolitic, and olivine-phyric shergottites (Goodrich 2002). Furthermore, the literature shows that martian bulk compositions are different from common terrestrial samples in several ways. For example, Papike et al. (2009) compared the bulk silicate compositions of Earth, Mars, the Moon, and Vesta (see Papike et al. 2009; their Tables 5 and 6) and showed that martian basalts are enriched in FeO and depleted in Al2O3 when compared to terrestrial samples. Papike et al. (2009) estimated that average martian basaltic compositions for Al2O3 and FeO were 6.55 and 18.0 wt%, respectively. We show similar contrasts between the two rock types using total FeO (FeOt) in liquids from partial melting experiments on martian bulk compositions, with an average of 16.6 ±4.29 wt% FeO, is compared to 8.60 ±3.15 wt% FeO, when terrestrial bulk...