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REVIEW

SPECIAL COLLECTION: OLIVINE

Rates and styles of planetary cooling on Earth, Moon, Mars, and Vesta, using new models for oxygen fugacity, ferric-ferrous ratios, olivine-liquid Fe-Mg exchange, and mantle potential temperature

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ABSTRACT

Mantle potential temperatures (T_p) provide insights into mantle circulation and tests of whether Earth is the only planet to exhibit thermally bi-modal volcanism—a distinctive signature of modern plate tectonics. Planets that have a stagnant lid, for example, should exhibit volcanism that is uni-modal with T_p, since mantle plumes would have a monopoly on the genesis of volcanism. But new studies of magmatic ferric-ferrous ratios ($X^{liq}_{Fe2O3}/X^{liq}_{FeO}$) (Cottrell and Kelley 2011) and the olivine-liquid Fe-Mg exchange coefficient, K_D(Fe-Mg)$^{Ol\text{-}liq}$ (or K_D) (Matzen et al. 2011) indicate that re-evaluations of T_p are needed. New tests and calibrations are thus presented for oxygen fugacity (f_{O_2}), $X^{liq}_{Fe2O3}/X^{liq}_{FeO}$, potential temperature (T_p), melt fraction (F), K_D, and peridotite enthalpies of fusion (ΔH_{fus}) and heat capacities (C_P). The new models for $X^{liq}_{Fe2O3}/X^{liq}_{FeO}$ and f_{O_2} reduce error by 25–30%, and residual error for all models appears random; this last observation supports the common, but mostly untested, assumption that equilibrium is the most probable of states obtained by experiment, and perhaps in nature as well. Aggregate 1σ error on T_p is as high as ~±77 °C, and estimates of F, and mantle olivine composition, are the greatest sources of error. Pressure and ΔH_{fus} account for smaller, but systematic uncertainties (a constant ΔH_{fus} can under-predict $T_{excess} = T_p^{plume}–T_p^{ambient}$; assumptions of 1 atm can under-predict T_p). However, assumptions about whether parental magmas are incremental, accumulated, or isobaric batch melts induces no additional systematic error.

The new models show that maximum T_p estimates on the oldest samples from Earth, Mars, Moon, and Vesta, decrease as planet size decreases. This may be expected since T_p should scale with accretion energy and reflect the Clausius-Clapeyron slope for the melting of silicates and Fe-Ni alloys. This outcome, however, occurs only if shergottites (from Mars) are 4.3 Ga (e.g., Bouvier et al. 2009; Werner et al. 2014), and the highest MgO komatiites from Earth's Archean era (27–30% MgO; Green et al. 1975) are used to estimate T_p. With these assumptions, Earth and Mars exhibit monotonic cooling, and support for Stevenson's (2003) idea that smaller planets cool at similar rates (~90–135 °C/Ga), but at lower absolute temperatures. T_p estimates for Mars and Earth are also important in two other ways: Mars exhibits non-linear cooling, with rates as high as 275–550 °C/Ga in its first 0.5 Ga, and Archean volcanism on Earth was thermally bi-modal. Several hundred Archean volcanic compositions are in equilibrium with Fo92–94 olivine, and yield T_p modes at 1940 and 1720 °C, possibly representing plume and ambient mantle, respectively. These estimates compare to modern T_p values of 1560–1670 °C at Mauna Loa (plume) and 1330–1450 °C at MORB (ambient). We conclude that plate tectonics was active in some manner in the Archean, and that assertions of an Archean "thermal catastrophe" are exaggerated. Our new models also show that the modern Hawaiian source, when compared at the same T, has a lower f_{O_2} compared to MORB, which would discount a Hawaiian source rich in recycled pyroxenite.

Keywords: Potential temperature, Mars, Vesta, Moon, secular cooling, mantle plumes, Archean, tectonics