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Using Mantle Potential Temperatures and Geodynamic models to understand the long-term Thermal and Tectonic Evolution of Terrestrial Planets

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A survey of the inner Solar System suggests that the Earth is the exception as it operates within a plate tectonic regime. Venus has the potential to be another such outlier, with its broad similarity to the Earth. However, while the Earth is the only body in the Solar System for which significant information about internal planetary processes and tectonics is retained and accessible, there remains significant uncertainty regarding the initiation and longevity of plate tectonics [e.g., 1]. Venus with its thick atmosphere and relatively young surface age is more of a geodynamic and geochemical enigma, with early-stage plate tectonics and stagnant or episodic states suggested [e.g., 2]. Its climate evolution is similarly argued, ranging from Earth-like to a constant thick and caustic runaway greenhouse state [e.g., 3]. The long-term tectonic and climatic evolution of a planet can be inferred from their thermal evolution, which can be derived from the volcanic record.

Basaltic volcanism recorded in the rock record, and measured by remote detection or direct sampling, reflects the internal temperature of the planet – the mantle potential temperature (T_P). Geochemically derived T_P, from well-established relationships between olivine composition and mantle temperature, are combined with robust numerical experiments of mantle convection and tectonics to determine the likelihood of a tectonic state at the time of melt generation. The numerical experiments allow for the determination of surface temperature at the time of formation, a proxy for the planet's climatic state [e.g., 1–4].

We show that Earth's evolution is consistent with a plate tectonic regime since 3.8 Ga, as expected. Within high probability, Venus' evolution is consistent with an early phase of plate tectonic-like activity that perhaps lasted until ~ 1 Ga and was followed by a stagnant lid-like state, consistent with current observations. Venus' climate results suggest an early runaway greenhouse state is likely for early plate tectonic-like states, in agreement with [4]. We will discuss these implications and discuss results for Mars and Mercury.

[1]Weller and Lenardic. (2018) GeoSci. Front.
[2]Rolf et al. (2022) Space Sci. Rev.
[3]Gillmann et al. (2022) Space Sci. Rev.
[4]Weller et al. (2023) Nat. Astr.