DETECTABILITY AND SCIENTIFIC IMPLICATIONS OF CRUSTAL REMANENT MAGNETISM ON THE SURFACE OF VENUS. J. G. O’Rourke¹, C. Gillmann², P. Tackley³, J. Buz⁴, R. R. Fu⁵, R. J. Lillis⁶. ¹School of Earth and Space Exploration, Arizona State University, Tempe, AZ (igorouk@asu.edu). ²Department of Geosciences, Free University of Brussels, Belgium. ³Department of Earth Sciences, ETH Zurich, Switzerland. ⁴Department of Physics and Astronomy, Northern Arizona University, Flagstaff, AZ. ⁵Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA. ⁶Space Sciences Laboratory, University of California, Berkeley, CA.

Introduction: Spacecraft missions have all failed to detect an internally generated magnetic field at Venus—the upper limit is $10^{-5}$ times Earth’s magnetic moment from Pioneer Venus Orbiter (PVO) [1]. The standard explanation for the lack of a dynamo today is that the core is cooling too slowly to convect [2]. Although the core remains at least partially liquid, heat transport occurs via thermal conduction without driving vigorous fluid motions. However, the core likely cooled more rapidly in the past when it was hotter. Venus rotates slowly compared to Earth, but still fast enough for a dynamo (e.g., with a small Rossby number in the core). Our simulations (Fig. 1) showed that Venus may have hosted an Earth-strength magnetic field that survived until recently—within the surface age [3]. Evidence for an ancient dynamo would test two hypotheses that presently lack direct support [3]:

1. The core is chemically homogeneous, and likely contains light elements (Si, O, Mg, etc.) that powered chemical convection until recently. Venus suffered a late energetic impact that mechanically mixed the core—removing chemical stratification that could otherwise prevent convection [4].

2. Surface temperatures have remained below the Curie points of common magnetic minerals. Climate has been stable, without catastrophic excursions, but possibly with gradual heating [5,6].

Here, we show that signatures of ancient magnetism could remain preserved in the crust and detectable by future missions such as with aerial platforms. Locations of magnetized crust would also reveal the stratigraphic history and relative ages of the surface.

Methods: We perform calculations to estimate the magnetic signature of crustal remanent magnetism on the surface. First, we consider the stability of magnetic carriers at Venusian temperatures. Thermal gradients in the lithosphere set the maximum thickness of magnetized crust. Second, we compute radial magnetic anomalies produced by various geometries of magnetized crust at operating altitudes for aerial platforms.

Stability of magnetized grains: Crustal rocks on Venus are expected to contain ferrimagnetic minerals by analogy to terrestrial basalts. Emissivity variations at ~1 μm have been attributed to the weathering of magnetite in fresh basalts to hematite [7]. Lava and magma that cooled in the presence of a magnetic field on Venus would have acquired a thermoremanent magnetization (TRM). However, elevated surface temperatures hinder the preservation of TRM on Venus in comparison to Earth. For an ellipsoidal, single-domain grain, the magnetic relaxation time is $\tau = (1/v_0) \exp(\Delta M B_s/(2k_B T))$, where $v_0 \sim 10^{10}$ Hz is a lattice vibrational frequency, $v$ is grain volume, $M_s$ is saturation magnetization, $B_s$ is coercivity, $k_B$ is Boltzmann’s constant, and $T$ is temperature. Experiments show that $M_s$ drops rapidly as $T$ approaches the Curie point: ~580 and 675 °C for magnetite and hematite, respectively [8]. The surface of Venus is ~462 °C at the average elevation, and the atmospheric lapse rate is ~10 °C/km.

We compute the volume of Venustian crust capable of preserving remanent magnetization over geological timescales. Thermal gradients within the crust of Venus are extremely uncertain. Based on the assumption that the core is cooling too slowly to convect [2], the core may remain Earth-like for ~4 Gyr but not today.
that the basalt-eclogite phase transition limits crustal thickness, an inversion of gravity and topography data indicated that average geothermal gradients are $<15$ °C/km, and typically $\sim5$–10 °C/km [9]. However, thermal gradients may exceed $\sim24$ °C/km near geologic features associated with rapid heat flow such as coronae [10]. Therefore, the distance from the surface to the depth of the Curie point for magnetite is typically $\sim10$–20 km but may be as far as $\sim33$ km (e.g., starting from elevations) or as short as $\sim5$ km.

**Detecting magnetized crust:** The magnetic anomaly associated with a vertical cylinder in the crust is

$$\Delta B_z = \frac{1}{2} \mu_0 \Delta M_z \left[ \frac{z + L}{\sqrt{(z + L)^2 + R^2}} - \frac{z}{\sqrt{z^2 + R^2}} \right]$$

where $\mu_0$ is vacuum permeability, $\Delta M_z$ is magnetization intensity, $z$ is observational altitude, $L$ is the thickness of the cylinder (e.g., from the surface to the depth where temperatures reach the Curie point), and $R$ is the radius of the cylinder. We assume that $\Delta M_z = 3$ A/m as in typical terrestrial basalts. Magnetospheric and ionospheric currents and lightning may create confounding magnetic fields near the surface, in addition to any fields intrinsic to a spacecraft. We adopt $\sim40$ nT as a nominal noise floor for realistic measurements.

**Results:** Simulations predict $>100$ km of melt production (assuming $\sim10\%$ extrusive) during the past $\sim1.5$ Gyr of sporadic dynamo activity (Fig. 1). Magnetite grains $>38$ nm in diameter may retain TRM for $>1$ Gyr at $462$ °C (Fig. 2), assuming length-to-width ratios of $1.3:1$. Smaller grains of magnetite at higher elevations (e.g., Maxwell Montes) or hematite at any elevation could also retain TRM [8]. Larger single vortex grains are expected to retain remanent magnetization for $>1$ Gyr even at elevated temperature [11].

**Suitability of aerial platforms:** A recent study concluded that a variable altitude platform operating at $\sim50$–60 km could complete myriad high-priority investigations related to climate and surface history [12]. Because ambient temperatures at those altitudes are $<60$ °C, required sub-systems have at least moderate technical maturity [12]. Predicted magnetic anomalies are $>40$ nT for vertical cylinders that are $>10$ km thick and $>25$ km in radius (Fig. 3). If $R = 100$ km, then the critical thickness for detectability drops to $L > 3$ km. Decreasing the noise floor to $\sim10$ nT would further reduce the critical thickness to $<1$ km, enabling the discrimination of magnetization in individual flows.

Prior missions could not detect small magnetized regions. For instance, PVO reached $\sim150$ km periastris near the equator and thus was not sensitive to magnetizations at smaller spatial scales than this within $\pm50^\circ$ latitude, or at any reasonable scale near either pole.

**Conclusions:** Any detection of crustal remanent magnetism would provide unique constraints on the formation and evolution of Venus. Simulations indicate that a substantial volume of crust formed while Venus hosted an Earth-strength magnetic field. Even after one billion years, magnetite and hematite grains with sizes widely observed in volcanic rocks could retain thermoremanent magnetism. Thermal gradients of $\sim10$ °C/km in the lithosphere limit the maximum thickness of magnetized crust to $<35$ km, but predicted magnetic anomalies remain above projected detection limits for an aerial platform in a nominal altitude range. A magnetometer survey under the ionosphere would also enable electromagnetic sounding to constrain the internal structure and dynamics.


**Figure 2** | Magnetite can retain TRM on Venus. Reasonably sized, single-domain grains have relaxation times $>1$ Gyr. Hematite retains TRM for a wider range of grain sizes since its Curie point is $\sim95$ °C higher.

**Figure 3** | Aerial platforms could detect magnetized crust. Predicted anomalies are above a conservative noise floor at a nominal altitude range ($\sim50$–60 km) for cylindrical thicknesses $>10$ km and/or radii $>25$ km.