MYSTERY OF INTRUSION HISTORY AT SYRTIS MAJOR: CLUES FROM MULTIPLE DATA SETS

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Syrtis Major overview: Syrtis Major is a large (~1100 km diameter), low-relief volcanic construct near the edge of the Martian global dichotomy boundary. The most recent visible major flows on its flanks date approximately to the Hesperian epoch, around 3.5 Ga. The caldera complex is approximately 300 km x 150 km, elongated approximately NNE to SSW and implying collapse into a vast, at least partially-evacuated magma chamber. Different sub-calderas 230 Ma to 3.8 Ga, indicate a long-lived volcanic system [1, 2, 3]. We are interested in constraining the size of the magma chamber, the total volume of magma intruded and extruded, and the compositional evolution of the magma.

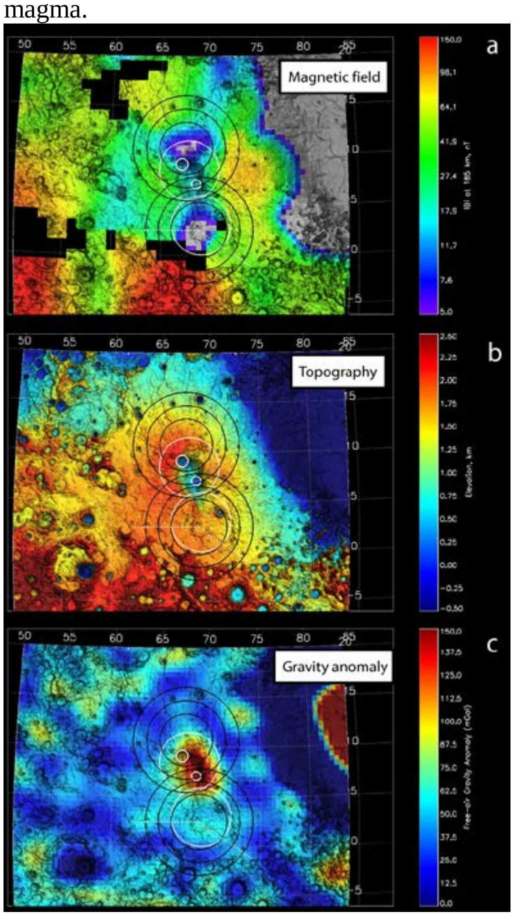

Fig 1: maps of Syrtis major showing a) magnetic field at 185 km, b) topography, c) free air gravity anomaly. The small white circles are the calderas of Meroe (northmost) and Nili (southmost) Paterae. The larger white circles represent high-density cylindrical loads modeled to fit the gravity anomaly data. The large black circles represent cylindrical areas of magmatic intrusion (with uncertainties) modeled to fit the magnetic field data.

Thermal demagnetization by magmatic intrusion: Martian crust which has been demagnetized by magmatic intrusion in the last ~4 Ga cannot have subsequently acquired, upon cooling, any substantial thermoremanent magnetization (TRM), due to the probable lack of a global magnetic field since then [4, 5]. Therefore when we examine orbital maps of crustal magnetic field, magmatic activity <4 Ga ago significant enough to cause thermal demagnetization on scales larger than the altitude of measurement will result in reduced field amplitudes (without the terrestrial complications of induced magnetization, TRM or subtracting a global field).

Thermal-magnetic modeling. We intrude magma stochastically as dikes and sills over 500 Ma into a half space using a 2-D finite volume method [6]. Individual intrusions are accommodated by displacing the surrounding crust to conserve mass, and we record the maximum temperature ever reached at each location in the crust over the subsequent 500 Ma. We then define a stochastic magnetization pattern with a characteristic vertical and horizontal coherence length [7] and a direction parallel/anti-parallel, 45° to the vertical, consistent with global field reversals (the direction is found not to be important for our purposes). We apply experimental curves for thermal demagnetization of TRM of 3 magnetic minerals with different blocking temperatures (pyrrhotite-325°, magnetite 580°C, hematite 670°C) [8]. This results in a partially demagnetized half space. For adequate statistics, we apply this 200 times for each combination of magnetization coherence wavelength, magnetization strength, intrusion rate, intrusion radius and blocking temperature, for a total of ~5 million forward models.

Magnetic results: We then calculate the χ^2 goodness-of-fit for each of the models to both the northern and southern areas of low magnetic field and consider all those within the 1-Sigma error hyper-ellipsoid to be acceptable fits. Figure 2 shows the B_{185} data and the family of acceptable model curves, as well as means and standard deviations of intrusion radius and total intrusion volume corresponding to these acceptable fits, separately for each of the 3 magnetic minerals and coherence wavelengths.

We notice that the best fits tend to occur for smaller magnetization coherence wavelengths, also favoring a lower Curie temperature magnetic mineral. The best-fit intrusion radii are around 210-230 km.

Gravity modeling. The Syrtis major gravity anomaly is mostly confined to the area beneath the caldera. The bulk of the dense material is located between 4° and 11° north. Figure 3 shows that the gravity data is best fit [9] by flexurally-supported topography and a cylinder of higher-density material 5-10 km thick (for likely density contrasts) and 175 km in radius, centered at 7.5° N, 68.7° E.

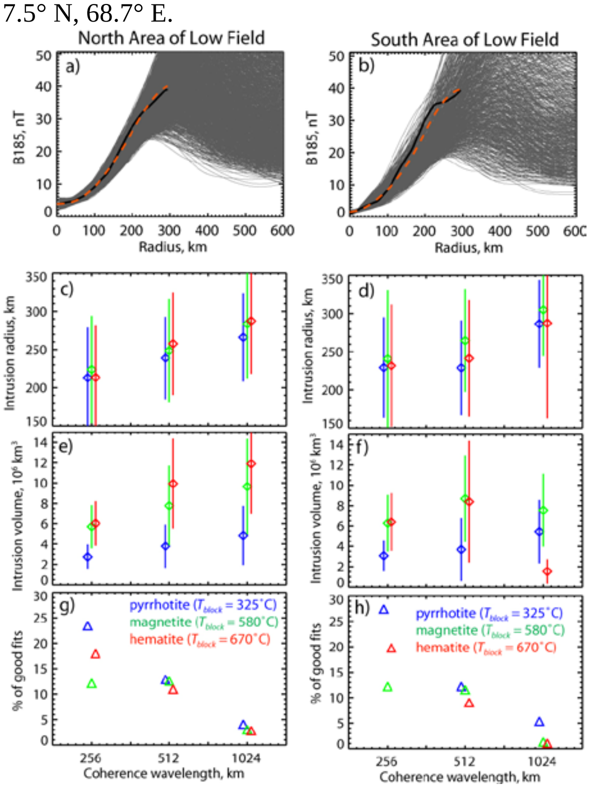

Figure 2: The top row plots azimuthally-averaged radial profiles of measured B185 (black), compared with all simulated profiles within 1 Sigma of the χ^2minimum (gray), i.e. the 'good' fits. The best individual fit is shown as an orange dotted line. Panels c) and d) show the mean and standard deviation of the intrusion radius for each of the good fits shown in the top row, separately for each of the 3 blocking temperatures and coherence wavelengths. Panels e) and f) show this for the intrusion volume above the Curie isotherm. Panels g) and h) show the distribution of the good fits among the blocking temperatures and coherence wavelengths.

Why the different gravity and magnetic signatures? If all the intruded magma were mafic (i.e. of mantle origin), one would expect a strong correlation between the intrusion volumes/locations implied by gravity and magnetic data. However, while the southern low magnetic field area implies substantial intrusions over an area ~400 km in diameter centered around ~3°N, the gravity data implies little or no density contrast between the surrounding crust and any intrusion south of the caldera complex, suggesting lower density magmas there. Similarly, the northern low magnetic field area implies intrusion offset ~100 km north of the dense buried load implied by the gravity data (figure 3), implying that there was substantial magmatic intrusion north of 10°N comprised of lower density material than is responsible for the major gravity anomaly at 7° N.

Link to Petrographic Observations.
Recent spectral ovservations from CRISM indicate that regions of exposed rock in the Nili Patera caldera are silicic (<5 % mafic phases) consistent with rhyolitic eruptive products or granitic intrusions [10]. Thermodynamic modeling of shallow upper crustal magma intrusions indicate a more likely prolonged fractional crystallization mechanism for the production of these magmas as compared to crustal melting [10]. Fractional crystallization would leave a substantial dense crystal residue of mafic phases in the mid-crust, and would require long period of time at low melt fraction which is consistent with the gravity, magnetic and thermal modeling of magmatic intrusions.

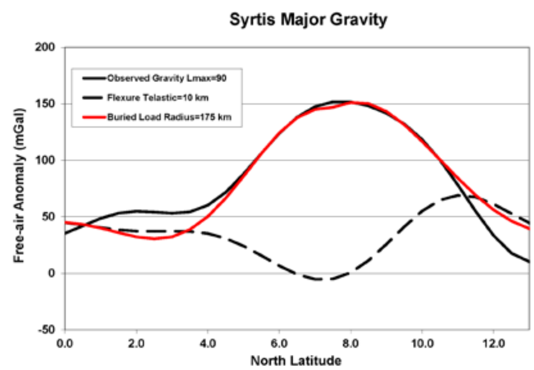

Figure 3: the Syrtis major gravity anomaly (red) is best fit by a model that includes both the flexurally support topography and a dense subsurface load (black solid line).

Conclusions: Magnetic field, gravity and mineralogical data imply a complex eruptive history at Syrtis. This likely involved long-lived magmatic activity beneath the main caldera complex resulting in fractional magma crystallization and the accumulation of dense material. However, if magmatic activity south of the caldera is the source of the low magnetic field there (as opposed to an uplifted and infilled impact crater), the magma must have been less dense, implying faster crustal melting without fractionation.

References: [1] Plescia et al., *JGR*, 2002. [2] Lillis et al., *GRL*, 2008. [2] Hiesenger & Head, *JGR*, 2004. [3] Williams et al., *JGR* 113. [4] Lillis et al., *JGR*, 2013. [5] Lillis et al., *GRL*, 2008. [6] Dufek and Bergantz, *J. Petrology*, 2005, 2009. [7] Lillis et al., *JGR*, 2010. [8] Dunlop, *GJI*, 2009 [9] Kiefer, EPSL, 2004 .[10] Wray et al, Nat. Geoscience, 2013.