MAGMATIC HISTORY OF SOUTHWESTERN THARSIS: CLUES FROM VOLCANIC HISTORY, THERMO-MAGNETIC MODELING AND ELECTRON REFLECTION MAGNETOMETRY. R. J. Lillis[1], J. Bleacher[2], J. Dufek[3], M. Manga[3] and R. Greeley[4], [1]UC Berkeley space sciences laboratory (rlillis@ssl.Berkeley.edu), [2]NASA Goddard space flight Center, [3]UC Berkeley Department of Earth and Planetary Sciences, [4]Arizona State University.

Introduction: 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 lack of a global magnetic field since then [1, 2]. Therefore, when we examine orbital maps of crustal magnetic field, magmatic activity <4 Ga old (if it results in thermal demagnetization on scales larger than the altitude of measurement) will cause reduced field amplitudes, without the terrestrial complications of induced magnetization, TRM, or the need to subtract a global core-generated field.

Electron Reflection (ER) Magnetometry is based on the magnetic mirror effect, that is, the reflection of charged particles from regions of increased magnetic field strength [3]. By comparing the pitch angle distribution of electrons moving toward the planet with the distribution of those electrons reflected from the planet, the increase in the magnetic field strength can be determined, resulting in a map of the field magnitude **|*B*|**, due to *crustal* sources only, at 185 km altitude (the mean altitude at which the electrons' scattering depth reaches unity), with a detection threshold for unambiguously crustal fields of 1-2 nT in the Tharsis region [4]. We refer to this as *B185*.

Tharsis tectonic history. Structural mapping of compressional ridges and radiating graben around Tharsis suggests at least five major stages of long-lived, magma-driven tectonic activity throughout Martian history, in areas not only associated with central volcanic constructs [5]. Figure 1 shows the ER map of Tharsis with the centers of this tectonic activity (numbered). Tectonism peaked in the Noachian and was centered in Claritas Fossae, still a strongly magnetized region, consistent with an early dynamo magnetic field being present at that time. The 2nd- 4th stages show decreasing tectonic activity from the late Noachian to early Amazonian eras, with primary centers in Thaumasia, SouthValles Marineris, Syria Planum and Alba Patera. The fifth stage occurred in the late Amazonian, somewhere beneath the Tharsis Montes [5, 6, 7]. These latter stages progressively demagnetized the Tharsis crust, though instead of partial demagnetization (leaving up to 1.0 A/m), as suggested by Johnson and Phillips [8], we suggest near-complete demagnetization as the ER map allows us to place an upper bound of ~0.1 A/m on the magnetization over most of Tharsis, assuming 200 x 200 x 40km uniformly magnetized blocks.

Demagnetization near Arsia Mons. We concentrate on the last stage of tectonic activity. During this time, magmatic intrusions are likely responsible for the magnetic boundary between magnetized and demagnetized crust near Arsia Mons. This is an ideal place to study effects of thermal demagnetization because the magnetic signature of the relatively recent intrusions has not been subsequently altered by large impacts. Figure 2 shows this boundary and how it neatly wraps around the caldera of Arsia Mons. Profiles of *B185* across this boundary show how sharp it is, particularly to the immediate west of the volcano, with a half-wavelength of ~100 km, close to the shortest wavelength sensitivity of magnetic measurements at these altitudes [9]. The question arises: what can the shape of these profiles tell us about the crustal magnetization (i.e. the nature of the magnetic boundary) and the volume of intruded magma necessary to explain the observations? With the same simple assumptions for magnetized blocks as above, the magnetization must decrease from ~3-5 A/m to <0.05 A/m across the boundary. However, to adequately approximate the physics of magnetization and magmatic intrusion, we need to take a more rigorous approach.

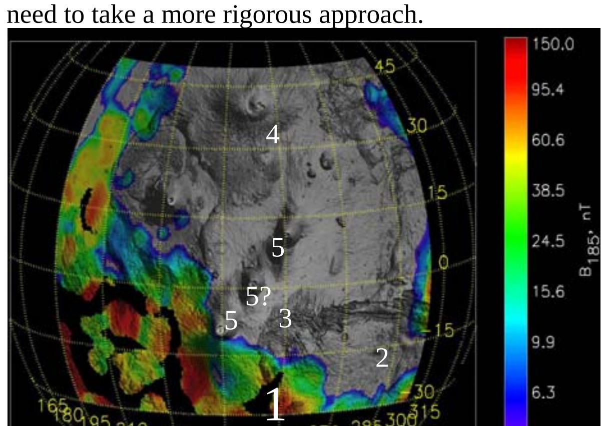

Fig 1: Tharsis ER map of crustal magnetic field at 185 km altitude overlaid on MOLA topography, with five mapped tectonic centers from Anderson et al. [8].

Modeling thermal demagnetization. We intrude magma stochastically over 100 Ma into a half space using a 2-D finite volume method [10]. Intrusion is accommodated by extension or crustal thickening, and we record the maximum temperature ever reached at each location in the crust. We then lay down a 'checkerboard' pattern of blocks of a given size (i.e. coherence length), magnetized randomly in one of two opposite directions consistent with global field reversals.

We set to zero the magnetization of all areas wher $T > T_{blocking}$ for a particular mineral (pyrrhotite, hematite, magnetite), then calculate the predicted values of *B185*, as shown in figure 3.

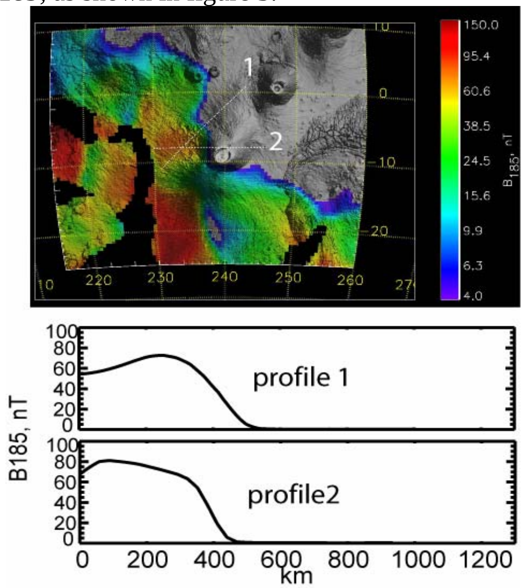

Figure 2: ER map of southwestern Tharsis displaying thermal demagnetization at Arsia Mons, with two sample profiles across the magnetic boundary.

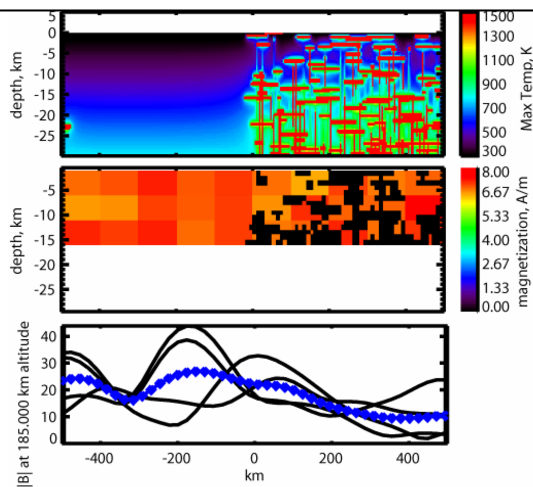

Figure 3: maximum temperature, magnetization strength and values of B185 resulting from stochastic magmatic intrusion. Black are individual runs and the blue diamonds are the average.

Fitting to the magnetic profiles. We considered the effects of all the main relevant parameters, varying:

1) magma volume
2) blocking temperature: 320°C, 580°C, 660°C
3) magnetizing field direction
4) magnetic coherence length
5) intrusion style (i.e.extension versus thickening)

We performed 500 of such runs for each combination of parameters and compared the results to profiles 1 and 2, minimizing the reduced χ^2 with respect to the parameters, averaged over all 500 runs.

Results: intrusion volume and magnetic coherence scale. We find that ~20 km³/km² of intrusion is required to completely demagnetize the crust, as shown in figure 4. This amounts to 80-90% replacement of the upper crust, depending on the magnetic mineral. Such intrusion volumes away from the large volcanic constructs cannot be explained by the volumes of magma represented in the fields of small, young volcanic vents between Arsia and Pavonis Mons (whose lava volumes total ~2500 km³) unless the intrusive-to-extrusive magma ratio is >200, which is unlikely according to terrestrial experience [11]. Many more such vents may be buried and those visible may represent the last stages of a period of extended magmatic upwelling in this part of Tharsis [12].

We also found that the coherence scale (i.e. the typical lateral extent of a coherently magnetized region) of the pre-existing magnetization must be <200 km. This places an important joint constraint on the formation rate of pre- or early-Tharsis crust and the rate of global magnetic field reversals during the dynamo era. To use an oversimplified example, if the crust formation rate is 10 cm per year, than the typical period of reversal would be < 2 Myr. We found that neither the style of intrusion, magnetization direction nor the blocking temperature could be meaningfully constrained in this analysis.

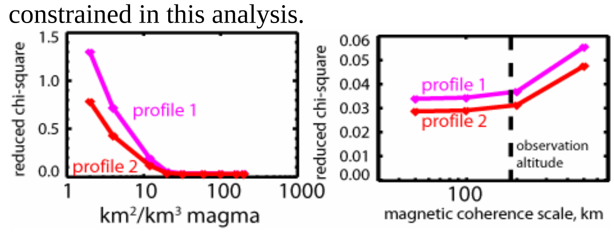

Fig. 4: mean χ^2 is plotted versus magma volume (left) and magnetic coherence scale (right).

Conclusions: The combination of volcanic mapping, thermo-magnetic modeling and orbital magnetic field data can place meaningful constraints on magmatic intrusion volumes and the coherence length of the pre-intrusion magnetization. In Tharsis, long-lived, pervasive magmatic upwelling is needed to explain these demagnetization signatures.

References: [1] M.H. Acuna et al., *Science* (1999). [2] R. J. Lillis et al., *AGU FM*, P12A-01 (2007), [3] Parks, Westview (2004), [4] R. Lillis et al., *Icarus* (2007), [5] Anderson et al., *JGR* (2001), [6] Mege and Masson (1996), [7] Wilson and Head (2002), [8] Johnson and Phillips, *JGR* (2005), [9] J. Connerney et al., *SSR* (2004), [10] Dufek and Bergantz, *J. of Petrology*, (2005), [11] S. M. White et al., *Geochem. Geophys. Geosys.*, (2006), [12] Bleacher et al., *JGRE* (2007).