Local spectral variability and the origin of the Martian crustal magnetic field

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[1] The crustal remanent magnetic field of Mars remains enigmatic in many respects. Its heterogeneous surface distribution points to a complex history of formation and modification, and has been resistant to attempts at identifying magnetic paleopoles and constraining the geologic origin of crustal sources. We use a multitaper technique to quantify the spatial diversity of the field via the localized magnetic power spectrum, which allows us to isolate more weakly magnetized regions and characterize them spectrally for the first time. We find clear geographical differences in spectral properties and parameterize them in terms of source strengths and equivalent-layer decorrelation depths. These depths to the base of the magnetic layer in our model correlate with independent crustal-thickness estimates. The correspondence indicates that a significant fraction of the martian crustal column may contribute to the observed field, as would be consistent with an intrusive magmatic origin. We identify several anomalous regions, and propose geophysical mechanisms for generating their spectral signatures. **Citation:** Lewis, K. W., and F. J. Simons (2012), Local spectral variability and the origin of the Martian crustal magnetic field, *Geophys. Res. Lett.*, *39*, L18201, doi:10.1029/2012GL052708.

1. Introduction

[2] Although planet Mars no longer possesses an internal dynamo, its crustal rocks contain strong remanent magnetization thought to have been induced by an ancient core-source field. The demise of this field is considered to have been a major event in the planet's geologic history [*Lillis et al.*, 2008], although many details remain poorly understood. As for Mars, a number of recent investigations have sought to constrain the existence and origin of lithospheric fields on Mercury and the Moon [*Langlais et al.*, 2010; *Shea et al.*, 2012]. Still, fundamental questions remain regarding the conditions in which planetary dynamos arise, evolve, and are recorded in the geologic record.

[3] The Magnetometer/Electron Reflectometer (MAG/ER) instrument aboard the Mars Global Surveyor (MGS) mission first mapped the global martian magnetic field from orbit, finding its distribution to be heterogeneous and particularly strong in the Terra Cimmeria region of the southern hemisphere [*Acuña et al.*, 1999]. Large, east-west trending structures in this region have been compared to the magnetic lineations found parallel to spreading ridges on the terrestrial seafloor [*Connerney et al.*, 1999], but have yet to be fully explained [*Harrison*, 2000]. Though several areas of the planet have been largely demagnetized [*Acuña et al.*, 1999], including large impact basins and the Tharsis volcanic province, the distribution of the field is generally poorly correlated with surface geology.

[4] In addition to its spatial distribution, the power spectrum of the magnetic field can provide information about the nature of the sources and formation processes. Previous authors have used the shape of the martian spectrum to estimate the strength and depth of the magnetic sources [*Voorhies et al.*, 2002]. However, the global spectrum is dominated by the most intensely magnetized regions of the planet, downweighting the signature of other areas, as shown by *Hutchison and Zuber* [2002] and W. E. Hutchison and M. T. Zuber (personal communication, 2012). We use the spatiospectral localization techniques of *Wieczorek and Simons* [2007] and *Dahlen and Simons* [2008] to map the magnetic characteristics of the Martian crust, showing that the crustal field exhibits localized magneto-spectral diversity among different geographic regions. This diversity enables enriched interpretation beyond that possible with fundamental, whole-sphere global spectral analyses.

2. Data and Methods

[5] In the absence of free currents ($\nabla \times \mathbf{B} = \mathbf{0}$), a scalar potential V can be defined whose gradient is the magnetic field $\mathbf{B}$. Here, we use the scalar potential field model of *Cain et al.* [2003], expressed in the spherical harmonic basis,

$$V = a\sum_{l=1}^{\infty}\left(\frac{a}{r}\right)^{l+1}\sum_{m=0}^{l}\left[g_l^m \cos m\phi + h_l^m \sin m\phi\right]P_l^m(\cos\theta), \qquad (1)$$

where P_l^m are the Schmidt-normalized Legendre functions, g_l^m and h_l^m the Gauss coefficients, and with colatitude and longitude (θ,ϕ). This model, complete to spherical-harmonic degree and order $(l,\ m) = 90$, is largely derived from low-altitude ($\sim$200 km) observations by MGS during the Aerobraking and Science Phasing Orbit mission phases, maximizing spatial resolution.

[6] To investigate the spatial variability of the field we perform a localized analysis of the global data using spherical windows known as Slepian functions [*Simons et al.*, 2006]. These bandlimited orthogonal functions are optimized to provide maximal concentration in the spatial domain. Multitaper spectral estimates are calculated using an eigenvalue-weighted sum of individually tapered spectra [*Dahlen and Simons*, 2008]. We use the Lowes-Mauersberger definition of the magnetic power spectrum,

$$S_l = (l+1)\sum_{m=0}^{l}\left[g_l^m\right]^2 + \left[h_l^m\right]^2, \qquad (2)$$

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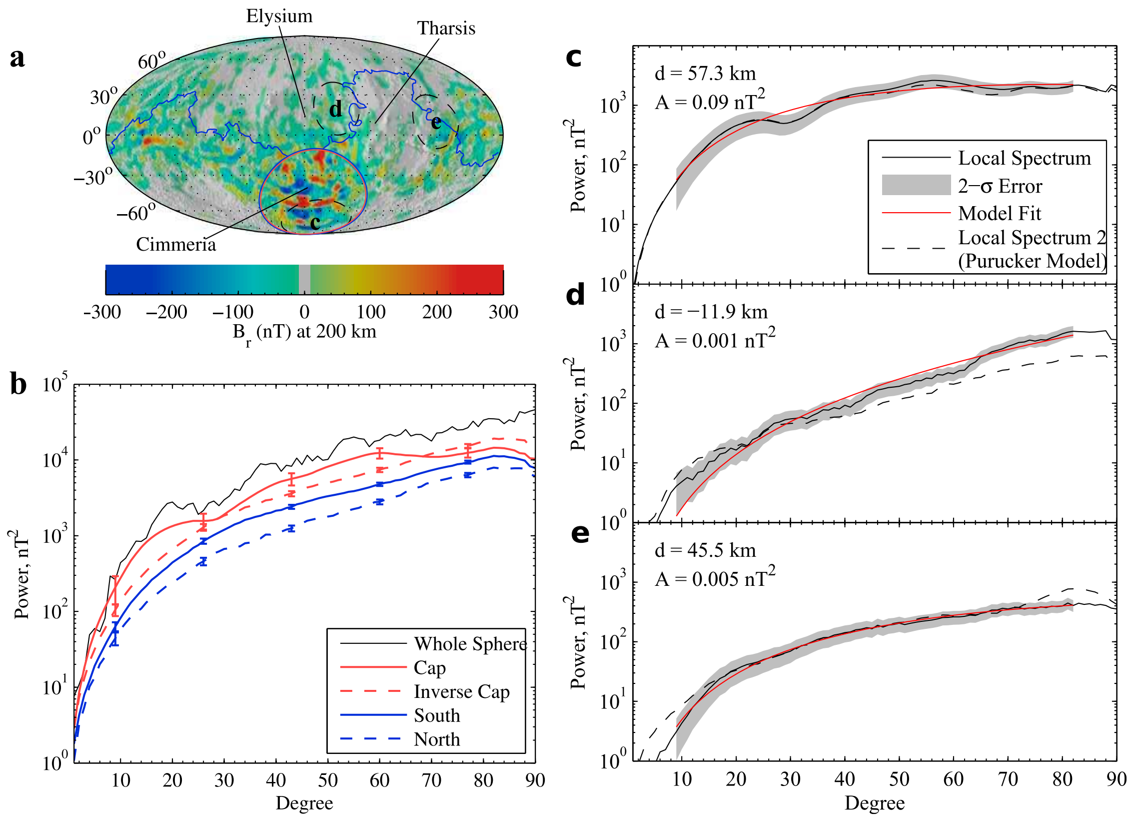

Figure 1. (a) Map of the martian radial magnetic field evaluated at 200 km, overlain on global shaded relief. Two boundaries used for separation of spatial regions are shown, a cap isolating strongly magnetized Terra Cimmeria region (red), and the dichotomy dividing the northern lowlands from the remaining southern hemisphere (blue). (b) Global magnetic power spectrum (black), compared to the spectra of the regions shown in Figure 1a. On the right, representative power spectra are shown from the set of 20° caps tiled over the martian surface. These locations span the range of modeled spectra including the (c) deepest and (d) shallowest shell depths, and (e) the spectrum best fit by the source model. Multitaper spectral estimates are shown in black, with the 2σ error range shown in gray. Fits for the modeled range L = 9–82 are shown in red.

which gives the mean-squared field amplitude per degree [*Lowes*, 1966]. The variance of the spectral estimates is computed under the moderately colored approximation, as described by *Dahlen and Simons* [2008]. As we refrain from estimating uncertainties in the potential model itself, this represents the *planetary* variance in a noise-free model.

[7] We begin by separating major regions of the planet to quantify the spatial variability that is apparent to the eye in Figure 1a. We isolate the highest-amplitude Cimmeria region by tapering over a spherical cap of radius 40° (shown in red), using tapers constructed with a maximum harmonic degree (bandwidth) of L = 8. Figure 1b shows the resulting spectral power for the cap over Cimmeria (Cap) compared to the rest of the planet (Inverse Cap). Roughly half the global magnetic field strength arises from the ~12% of the planet's surface area containing the Cimmeria region. Although the two portions contain roughly equal power, their spectra show subtle differences. The larger portion of the planet (excluding Cimmeria) is further divided across the hemispheric dichotomy (blue). We choose as a boundary the 45 km crustal thickness contour [*Neumann et al.*, 2008]. Using the algorithms outlined by *Simons et al.* [2006], we are able to construct optimally-concentrated windows for each of these irregular domains, again choosing a spectral bandwidth L = 8. Both the northern and southern fractions (excluding Cimmeria) comprise ~44% of the planet. The spectral shapes of these two portions are similar, though ~80% of the power resides in the south. From this initial analysis it is clear that the strongly magnetized region of the southern hemisphere greatly influences the global spectrum. The regional differences in spectral amplitude and shape hint at appreciable local information that global magneto-spectral analysis averages out.

3. Local Spectral Analysis Results

[8] To systematically map the magnetic power spectrum at a regional scale, we apply a moving window consisting of a spherical cap of radius 20°. Tapers were constructed with a spectral bandwidth L = 8, and a multitaper spectral estimate was derived using eigenvalue weighting of individual tapered spectra. This gives a Shannon number of 2.44, which roughly corresponds to the number of approximately uncorrelated spectral estimates that enable variance reduction of the multitaper spectrum. We derive spectra at 10° intervals on the sphere, although estimates are spatially correlated where their respective footprints overlap. Tapering reduces the spectral resolution, inducing covariance between points less than $2L$ + 1 degrees apart [*Wieczorek and Simons*, 2007; *Dahlen and Simons*, 2008].

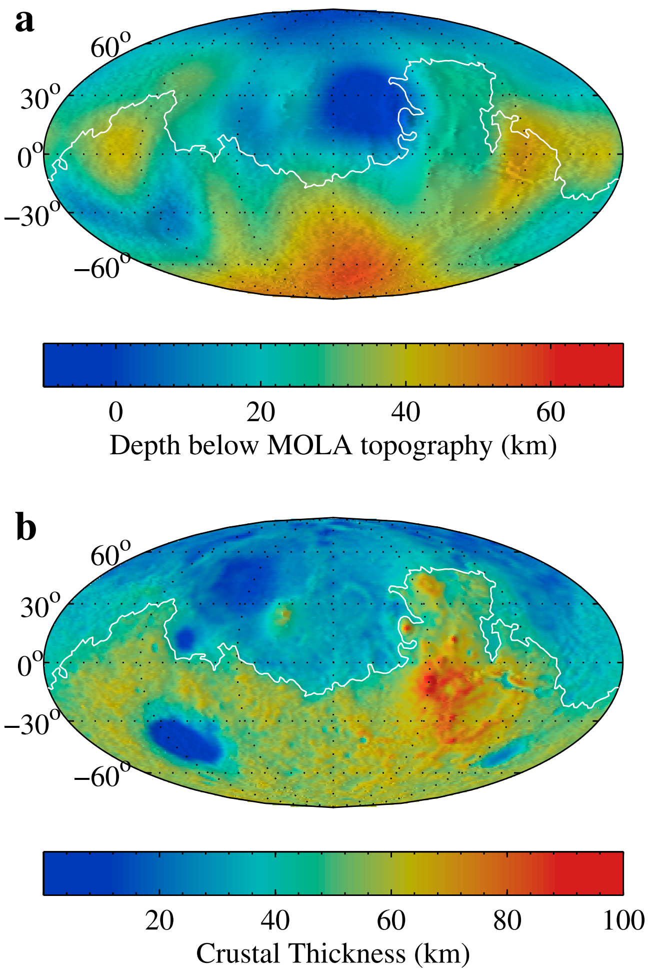

Figure 2. (a) Map of modeled source depths for the martian crustal magnetic field, relative to local planetary radius. (b) Regional variations show a correspondence with crustal thickness estimates for Mars, with greater model depths in the southern highlands.

3.1. Magnetic Source Model

[9] The shape of the magnetic spectrum contains information about the size, strength, and depth of the underlying magnetic sources. Although a number of physical source models have been proposed in the literature, we parameterize the spectra in terms of a spherical shell, at radius d, of randomly oriented point dipoles with an amplitude term A that is proportional to the mean-squared magnetization [*Voorhies et al.*, 2002], as follows:

$$S_l = Al(l+1/2)(l+1)(d/a)^{2l-2}, \tag{3}$$

where a is the reference radius and a–d is also known as the 'decorrelation' depth. This model generally overestimates the average depth of crustal sources which are in reality spatially correlated, and rather represents the base of the magnetic layer [*Voorhies*, 2008]. To avoid estimation bias in the first and last L degrees, this log-linear form is fit to spectra using degrees 9–82 only. In the regression we utilize the spectral covariance matrix as derived by *Dahlen and Simons* [2008] to properly account for the correlation between power estimates at adjacent degrees caused by tapering.

3.2. Inversion Results

[10] Analysis of the residuals shows that in over roughly 90% of the area of the planet the model provides a closer fit to the localized spectra than to the global spectrum, with the most strongly magnetized region of the southern hemisphere showing the largest departures from the model. As expected, locally estimated source amplitudes vary over several orders of magnitude across the planet. However, differences in spectral shapes also lead to widely varying depth estimates. Figures 1c–1e show several examples of localized spectra and their model fits (locations shown in Figure 1a), including those yielding the greatest (Figure 1c) and shallowest (Figure 1d) model depths. The spectrum best fit by the point source model is shown in Figure 1e, while Figure 1c is among the more poorly fitting locations. Overall, model fits largely fall within the 2σ range of the estimated spectra, shown in gray.

[11] The local magnetic spectra shown in Figures 1c–1e reveal spatial diversity which is averaged in the global spectrum. Figure 2a shows the full results of the local analysis, with model depths overlain on shaded topographic relief. Depth is referenced to the mean planetary radius within each localization region, as calculated from the Mars Orbiter Laser Altimeter (MOLA) data set (Figure S1 in Text S1 of the auxiliary material shows depths relative to the reference sphere).[1] Model depth estimates range from −11.9–57.3 km, as compared to the 46.7 km estimate of *Voorhies et al.* [2002] for the whole sphere. While negative depths are clearly unphysical, the estimated 2σ error range is comparable in magnitude at ±9.5 km. Although an unmodeled noise component from external fields could result in artificially shallower depths, it is noticeable that the shallowest model depths are not coincident with the weakest fields, where the signal-to-noise ratio should be at a minimum. Although we focus on the *Cain et al.* [2003] model, comparison with that of *Purucker et al.* [2000], which also incorporates low-altitude data, leads to similar results (Figures S2 and S3 in Text S1). Calculated depths differ by an average of 1.8 ± 8.9 km between the models, providing one estimate of the uncertainty inherent in the data. Truncating model fits to narrower degree ranges results in slightly greater average depths, though the relative variability is similar (Figure S4 in Text S1).

[12] While estimated depths vary across the planet, regions south of the hemispheric dichotomy are modeled as hosting deeper magnetic sources than the north, on average. Exceptions include regions around the Hellas and Argyre impact basins, which appear to have been largely demagnetized. On the whole, the spatial pattern of decorrelation depths corresponds well to models of crustal thickness from gravity and topography data, as shown in Figure 2b [*Neumann et al.*, 2008]. Noticeable departures from this correlation include the anomalous Cimmeria region, as well as much of the Tharsis volcanic province.

[13] Figure 3a shows the full range of model parameters found for the martian field. Here, individual data points have been resampled from the original grid onto an equal-area Fibonacci grid to show a representative distribution on the sphere. Significant differences are seen both in the amplitude and depth of modeled sources relative to the modeled

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL052708.

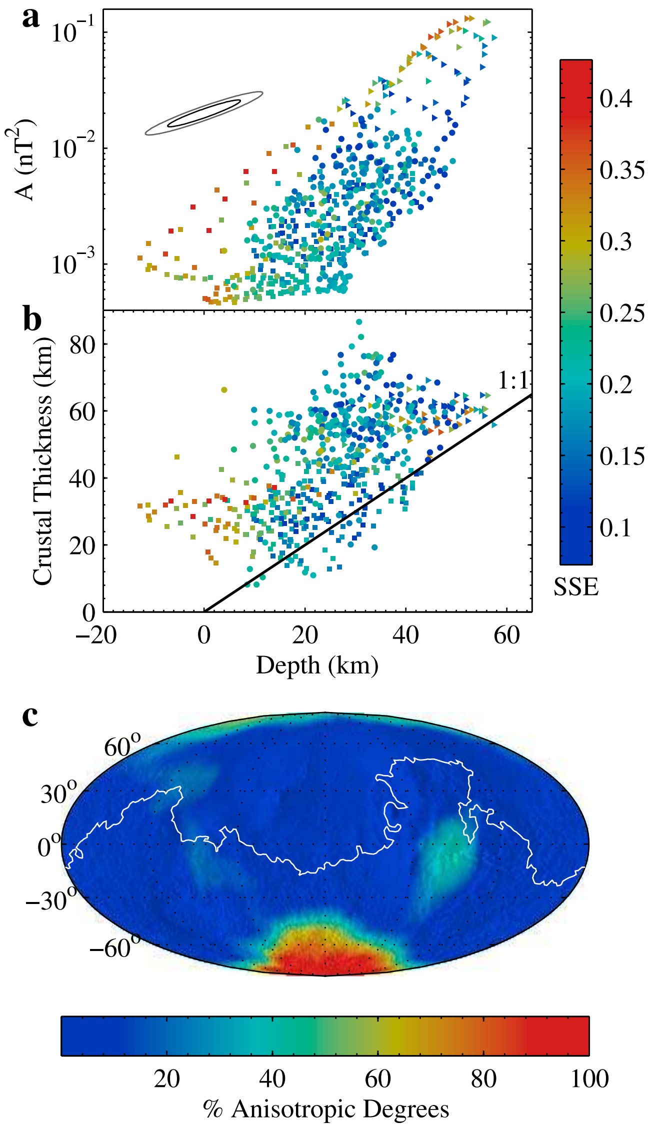

Figure 3. (a) Amplitude and depth parameter range of the martian crustal magnetic field for the point source model. Corresponding σ and 2σ error ellipses are shown to the upper left. Circle, square, and triangle markers correspond to points within the southern hemisphere, northern hemisphere, and Cimmeria cap, respectively. (b) Modeled depths compared to independently derived crustal thickness estimates. (c) Map of the percentage of harmonic degrees at each location showing significantly anisotropic distributions. The Cimmeria region is clearly exceptional in this regard.

uncertainty (shown by σ and 2σ ellipses). In general, depth variations are positively correlated with source strength, a reasonable relationship if model depths are an indicator of the real thickness of the magnetic crust. Colors in both plots show the sums of squared residuals of the log-transformed data. Regions representing poor model fits include the greatest modeled depths in Terra Cimmeria, and an area of negative model depths in eastern Elysium Planitia. Figure 3b shows a more detailed view of the correlation between modeled depths and crustal thickness from the model of *Neumann et al.* [2008]. For the large majority of the planet the magnetic model depths lie above the corresponding estimated base of the crust, consistent with both mineralogical and thermal constraints [*Arkani-Hamed*, 2005]. However, given that crustal thickness itself is the result of an inversion, and any actual magnetic layer will have finite thickness, we view the overall correlation as the more significant observation. Regions which depart from the global trend include the thick but weakly magnetized crust in Tharsis, though these areas still provide adequate model fits.

3.3. Anisotropy and Lineations

[14] An assumption of our analysis is that the magnetic sources at depth are uniformly randomly positioned and oriented [*Voorhies et al.*, 2002]. However, the well-known lineations that can be seen in portions of the southern hemisphere appear to show distinct anisotropy and large-scale coherence. Furthermore, *Connerney et al.* [2005] presented evidence for near-global occurrence of linear magnetic features in the crustal field. To test for the presence of anisotropy in both the spatial and spectral domains we evaluate the distribution of the localized harmonic coefficients within a given degree. In the isotropic case, coefficients of varying order are assumed to be normally distributed. We use the Kolmogorov-Smirnov test to evaluate the null hypothesis that these values are normally distributed for each degree of our local models. Figure 3c shows the fraction of the degrees 9 through 82 for which we can reject the assumption of isotropy. In general, we find widespread consistency with an isotropic distribution, with the strong exception of the southern Terra Cimmeria region where we are able to reject the null hypothesis with 95% confidence for nearly every degree of the spectra. These results exemplify the uniqueness of this particular region of the planet, while validating the random-source model elsewhere.

4. Discussion and Implications

[15] The magnetic source model used here represents only one way of parameterizing the magnetic spectrum. More realistic models have been proposed, including those with finite-volume sources [*Voorhies*, 2008]. We have chosen the simplified two-parameter model recognizing that a localized analysis reduces the number of effectively independently estimated spectral degrees. Meaningful constraints on additional parameters likely require improved knowledge of the martian field. Here, we constrain two of the most important parameters, namely the depth and strength of magnetized bodies within the crust. It is clear that the globally-averaged magnetic spectrum is dominated by a few strongly magnetized regions. By deriving localized magnetic spectra, we are able to identify previously unrecognized regional diversity, and parameterize and model it via laterally variable decorrelation depths that capture some of the true variability in the thickness of the magnetic crust.

[16] Results of the local analysis reveal new details about the nature of the remanent field. Modeled source parameters vary dramatically among geographic regions, including a surprising 70 km span in estimated depths below the planetary surface. The observed correlation of source strength and depth gives new information about the causes of field strength variations on Mars. While increased strength could result from more intense magnetization of the crustal rocks, the trend that we see would instead imply an overall thicker magnetic layer. Much of the observed variability in the

martian field may thus reflect underlying changes in the vertical extent of magnetization.

[17] Several observations support the geophysical implications of our model results. The range of our model depths fits well within the 10–100 km determined by *Nimmo and Gilmore* [2001] from the extent of demagnetization of large craters. Their favored value of 35 km to the base of the magnetized zone assumes a uniform layer across the planet, but is broadly consistent with our mean shell depth of 26 km. Our depths are consistent with the Curie isotherms at 4 Ga (50 and 70 km for magnetite and hematite respectively, as estimated by *Nimmo and Gilmore* [2001]). However, the greatest depths (>50 km), found in the southern hemisphere, likely require further explanation.

[18] The correlation of magnetic depth with crustal thickness from gravity and topography further broadly supports this source model. Though both sets of values are estimates, nearly all of our values lie within a 2σ range of the crustal zone. A best-fit value for the relationship between the two gives a magnetic depth at 56% of crustal thickness. This average shell depth, near the crustal midpoint, may indicate an actual magnetized zone encompassing much of the vertical extent of the crust. If so, this is consistent with an intrusive model whereby magmatic dikes penetrate much of the crust and acquire thermo-remanent magnetization [*Nimmo*, 2000]. In contrast, chemical remanent magnetization models based on hydrothermal alteration predict a fairly consistent magnetized zone in the permeable upper $\sim$10 km of the crust [*Scott and Fuller*, 2004; *Lillis et al.*, 2008].

[19] A number of geological provinces stand out with distinct characteristics by our analysis. The Tharsis volcanic region, unique in many respects, has previously been shown to retain a weak but significant magnetic signature, particularly in the south [*Johnson and Phillips*, 2005]. Several hypotheses have been proposed for the origin and modification of Tharsis magnetism, including a more strongly magnetized Noachian crust, progressively demagnetized by magmatic activity. In this region we see the most notable departure from the global correlation with crustal thickness. Figure 2 shows that although southern Tharsis represents the thickest crust on the planet, magnetic depths are generally shallower (20–30 km) than in other parts of the southern highlands. The preferential demagnetization of the lower crust that this implies is consistent both with greater intrusive magmatic activity [*Johnson and Phillips*, 2005] and an enhanced thermal gradient in the region.

[20] The eastern half of Elysium Planitia is surprisingly distinctive in our analysis of the crustal field. This area contains the shallowest magnetic sources detected in our study, including portions which are modeled at up to 10 km *above* the planetary surface. As shown in Figure 3a, the modeled sources in this region are stronger than in other regions of the northern hemisphere, and hard to explain in terms of a lower signal-to-noise ratio. Although the random-source shell may be an imperfect representation of reality, the exceptionally strong power at high degrees in Elysium may be difficult to reconcile with any lithospheric model. We postulate that this is reflective of the limitations of the *Cain et al.* [2003] model at high degrees, possibly a result of incomplete low-altitude data coverage. No negative depths are found for the Purucker model, although this may be a result of its derivation from equivalent sources specified to lie on the reference sphere.

[21] Finally, the Terra Cimmeria region of the southern hemisphere, long recognized as anomalous due to its distinctive magnetic lineations, also stands out in our results. Model parameters for this region comprise the strongest and deepest magnetic sources. However, local spectra produce lower-quality model fits than those for the rest of the planet. More complex spectra here, as in Figure 1c, likely result from large correlated sources that violate our model assumptions, producing excess power at certain wavelengths. The suggestion of strong anisotropy, in particular, demonstrates the uniqueness of this region compared to the rest of the planet. Although the magnetic lineations often appear exaggerated in rectangular map projections, these results do show an inherent alignment of the field in this region. Examination of the localized spectra shows much of the power is concentrated in the low-order (near-zonal) harmonics at nearly all wavelengths. However, we see no evidence of significant anisotropy elsewhere on the planet, as shown in Figure 3c, in contrast to the results of *Connerney et al.* [2005]. The unusual spectrum and anisotropic distribution of power in Terra Cimmeria, in addition to its enhanced magnetism, point to an exotic (though not necessarily unrelated) geologic origin.

5. Summary

[22] Localized analysis of the martian crustal magnetic field reveals previously unrecognized power-spectral diversity. Varying spectral shapes suggest a change in depth to the magnetized bodies in the crust, interpreted here in terms of a two-dimensional random-source shell model. The observed correlation between model depths and crustal thickness is compatible with a distribution of magnetic carriers throughout the crustal layer, perhaps including dikes or other intrusive magmatic bodies. We are able to distinguish a number of regions which exhibit uncharacteristic magnetic spectra, which will require additional geological and geophysical investigation. Model differences point to regional variations in geologic origin and thermal evolution. Additional low-altitude measurements from the upcoming MAVEN mission will allow for further refinement of field models, particularly at high degrees. This should lead to a better understanding of the origin, evolution, and regional variability of crustal magnetism on Mars — and ultimately how the planet compares to other terrestrial bodies in this respect.

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Supplementary Figures for Lewis, K. W. and Simons, F. J. (2012),
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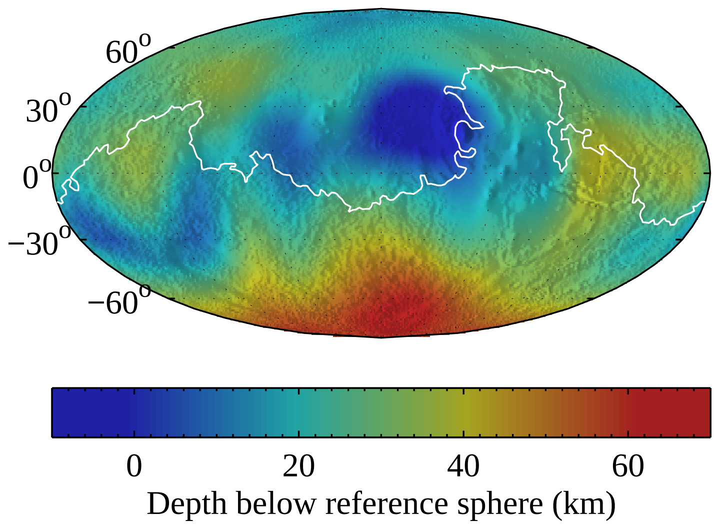

Figure S1: (a) Map of modeled source depths for the martian crustal magnetic field, relative to the reference sphere. Clearly, much of the variability in calculated model depths arises from power spectral diversity, although the inclusion of surface topography in Figure 1 alters these values slightly.

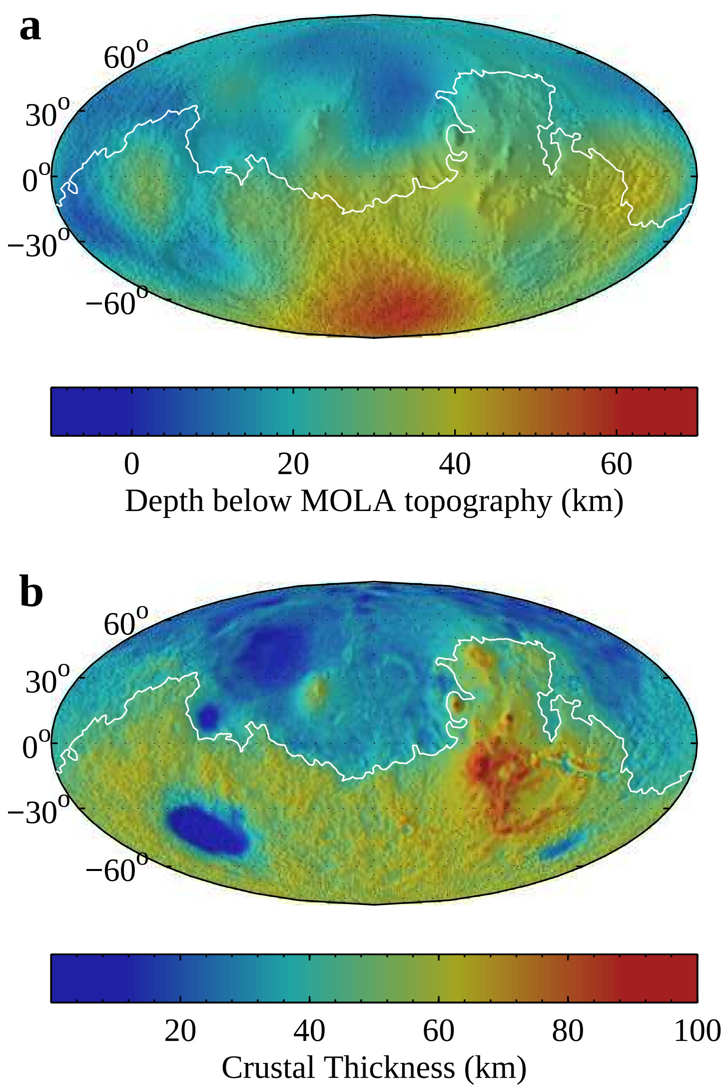

Figure S2: (a) Map of modeled source depths for the martian crustal magnetic field, relative to local mean planetary radius for the Purucker (2000) model. Regional variations show a correspondence with crustal thickness estimates for Mars, (b) with deeper modeled sources in the southern highlands.

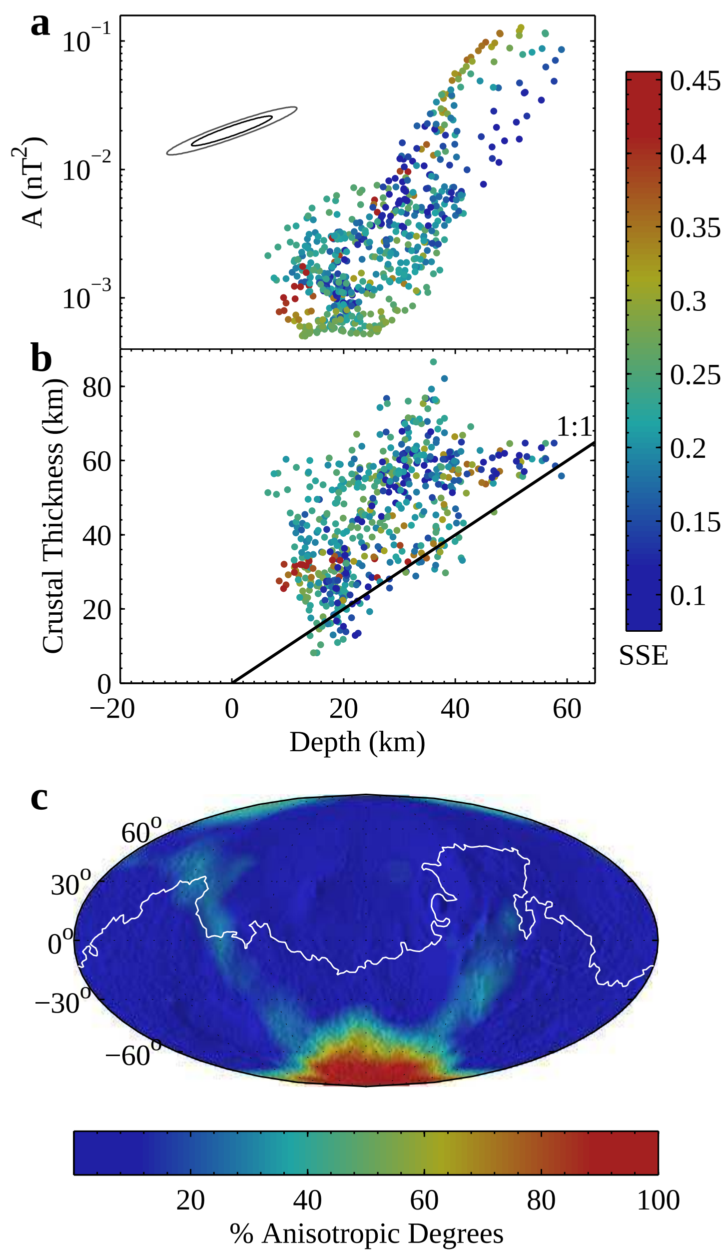

Figure S3: (a) Amplitude and depth parameter range of the martian crustal magnetic field for the spherical shell model for the Purucker (2000) model. Corresponding σ and 2σ error ellipses are shown in the upper-left. (b) Modeled depths compared to independently derived crustal thickness estimates. (c) Map showing the percentage of harmonic degrees at each location showing anisotropic distributions. The Cimmeria region is clearly exceptional in this regard.

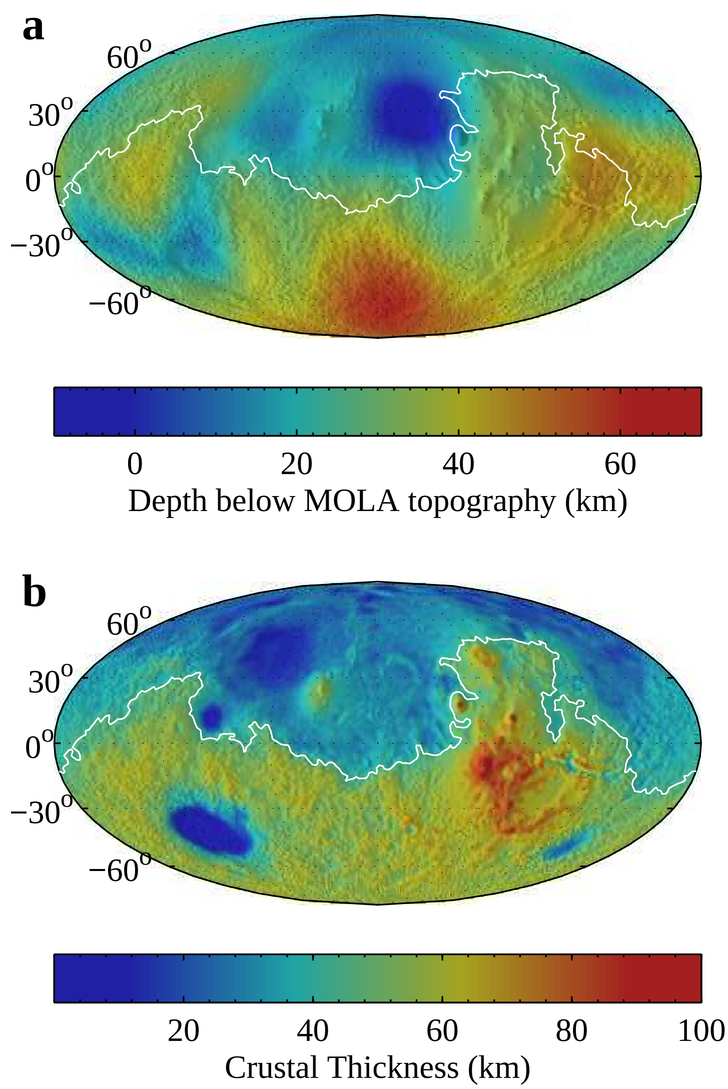

Figure S4: (a) Map of modeled source depths for the martian crustal magnetic field using only harmonic degrees [9:75], relative to local mean planetary radius. Regional variations show a correspondence with crustal thickness estimates for Mars, (b) with deeper modeled sources in the southern highlands.