A NEW, STATISTICALLY ROBUST TIMELINE FOR THE MARTIAN DYNAMO R. J. Lillis[1], S. Robbins[2], M. Manga[3], J.S. Halekas[1], H. V. Frey[4]. [1]UC Berkeley Space Sciences Laboratory (rlillis@ssl.Berkeley.edu), [2]Harvard University Department of Earth and Planetary Sciences, [3]UC Berkeley Department of Earth and Planetary Sciences. [4]Planetary Geodynamics Laboratory, NASA Goddard Space Flight Center

Impacts and crustal magnetization:
Large impacts on Mars (leaving craters >~300 km in diameter), alter the magnetization of the entire depth of crust over a geographic area comparable to the final size of the resulting crater [1, 2]. Excavation removes and reorients magnetized material within the transient cavity [3] while shock heating causes thermal demagnetization. Following the impact, as the new crust cools and any other crustal minerals heated above their Curie point can acquire a new thermoremanent magnetization (TRM) proportional to the strength of the local ambient magnetic field. In addition, unmagnetized materials can be magnetized in an external magnetic field through shock remanent magnetization (SRM) and existing magnetization can be reduced or erased if the minerals are shocked in an ambient field too weak to induce a sufficient SRM [4] Therefore, although the magnetic mineral fraction in post-impact crust can be affected by chemical processes like serpentinization [5] which depends on difficult-to-constrain variables such as water content, one can nonetheless argue that the magnetization contained within an impact crater is a reasonable proxy for the strength of the ambient magnetic field averaged over the crater cooling time (less than several million years [6]). Impact craters are thus useful in piecing together the history of Mars' ambient magnetic field.

What does a demagnetized crater look like?
Because it is impossible to uniquely invert orbital magnetic field data to determine subsurface magnetization, we instead use a Monte Carlo Fourier domain approach [7] and model statistically the magnetic field above magnetized and demagnetized craters, at 185 km and 400 km altitude (where magnetic field maps with global coverage exist). Figure 1 shows what average radial profiles of crustal magnetic field look like over demagnetized zones of 200-1000 km. We also use the useful metric $B_{in/out}$, i.e. the ratio of magnetic field measured within 0.5 crater radii and that measured between 1.25 and 2.0 radii, probability distributions of which are shown in figure 2 for craters which are completely, partially and not-at-all demagnetized.

We notice that 400 km altitude magnetic field data does not well-constrain crater magnetization. For example, a 400 km crater with $B_{in/out}$ = 0.83 at 400 km has almost equal likelihood of having zero magnetization or the same magnetization compared to its surroundings. In contrast, the same crater with $B_{in/out}$ = 0.83 at 185 km is all but certain to contain some magnetization and hence to have formed while the dynamo was still active. As can be seen, the larger the crater the more confidence we have in estimating its magnetization. This is the logic we apply to Martian craters with approximate ages derived from crater counting.

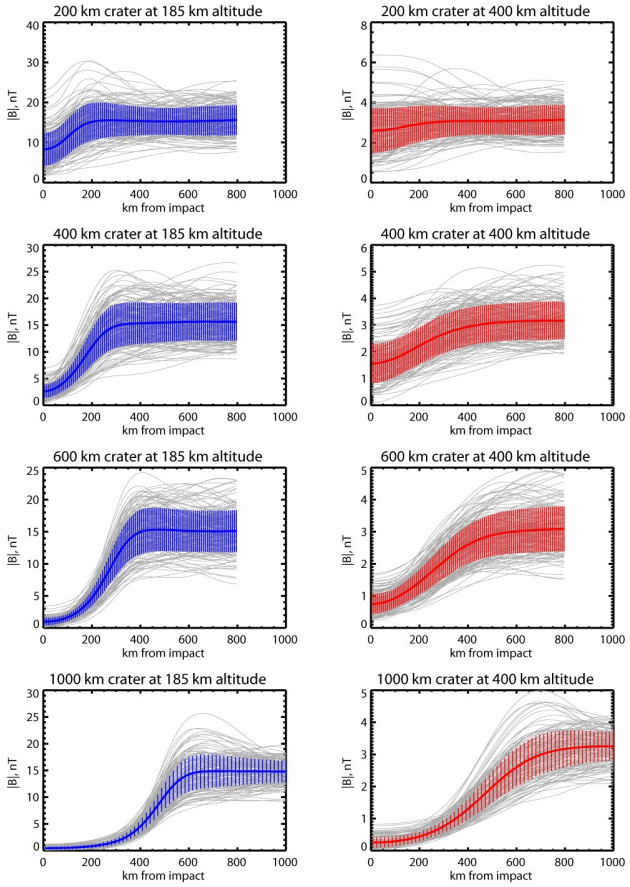

Figure 1: the circumferential averages of magnetic field intensity at 185 km at 400 km altitude above completely demagnetized circular zones of 200 km, 400 km, 600 km in 1000 km diameter are plotted as a function of radius. Red/blue solid lines and vertical error bars represent the mean and standard deviation of magnetic field profiles from 150 separate runs of our Monte Carlo magnetization model respectively. Light gray lines represent each run.

A new, statistically robust timeline for the Martian dynamo.
There are 36 craters/basins larger than 300 km for which a) the magnetic field measured outside the crater is high enough above the noise level that a

demagnetization signature can be detected and b) reliable ages have been derived [8, 9]. For each crater, we calculate the probability distribution of magnetization fraction and plot the distributions as a function of crater age in figure 3. A fraction of 1.0 means the crater has the same magnetization characteristics as its surroundings, while zero means it is completely demagnetized. We notice that figure 3a, showing only the basins >900 km in diameter, is consistent with the results of Lillis et al. (2008) [10]. The basins quite clearly fall into 2 groups: 1) 6 basins with essentially zero probability of containing any substantial magnetization: and 2) the remainder of the craters, all with probability distributions implying that they are at least partially magnetized and therefore likely having formed in the presence of a global magnetic field. These 2 basin populations do not overlap in age by more than a small fraction of the typical age uncertainty. Together they imply that the cessation of the Martian dynamo may have occurred around ~4.12 Ga, which was also the conclusion of Lillis et al. (2008) [10].

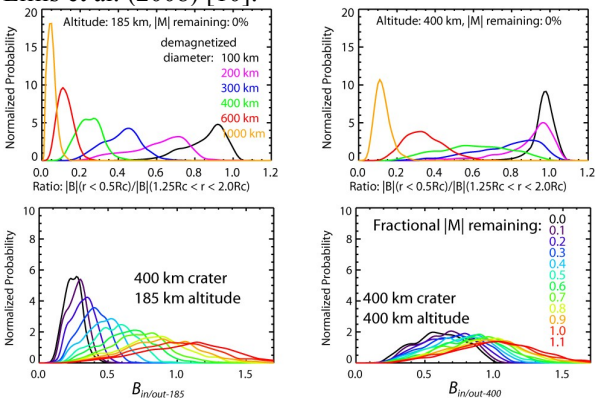

Figure 2: top row shows probability distributions of from demagnetized craters of various sizes. The bottom row shows distributions from a range of partially demagnetized craters of 400 km diameter.

The interpretation is somewhat less clear if we examine the smaller craters in isolation, as shown in figure 3b. This is partly because the magnetization distribution functions are wider than those of the larger craters (as is expected for smaller craters) and partly because the interpretation is quite different depending on whether we believe that the isochron ages of Schiaparelli, Newton and gamma are accurate formation ages or are younger ages due to resurfacing events subsequent to crater formation. For example, if these ages were reliable and ignoring for a moment the timeline strongly implied by the larger craters in Fig 3a, Schiaparelli and Newton's distributions imply magnetization (and therefore an active dynamo) at ~3.92 and ~4.00 Ga respectively. However, if Schiaparelli and Newton are ignored, as we believe appropriate based on their lack of a pristine crater rim, then the large uncertainty in the age of Cassini (4.00-4.16 Ga, see table 1a) allows for no basin magnetization (and therefore no dynamo) after ~4.1 Ga. Even if the gamma crater (whose rim also suffers from probable resurfacing) is included, its age range of 3.98-4.11 Ga similarly does not preclude a dynamo cessation at 4.1 Ga.

Therefore, while magnetic field data does allow for the possibility of a global magnetic field on Mars later than 4.0 Ga, we believe the preponderance of evidence implies that the Martian dynamo and global magnetic field ceased sometime around 4.1 Ga and did not recommence. Since a global magnetic field likely shielded the atmosphere from significant solar wind erosion, this timeline has important consequences for Mars' climatic evolution history.

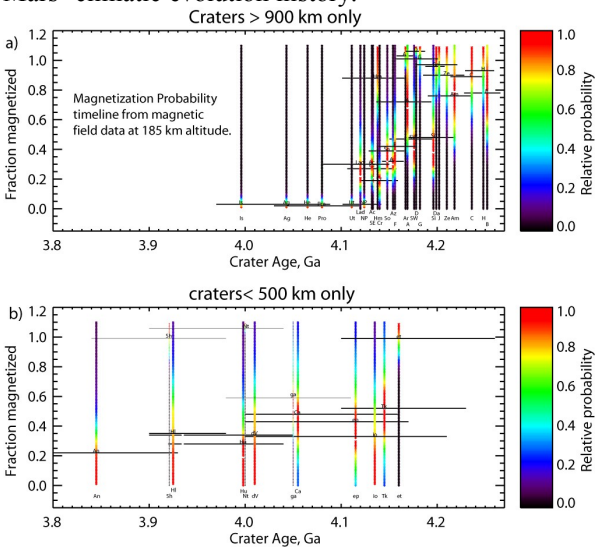

Figure 3: Magnetic probability timeline of large craters formed on early Mars, calculated from the electron reflection map of crustal magnetic field magnitude at 185 km altitude [Lillis et al., 2008b]. The text symbols are contractions of the full crater names listed in table 1. Magnetization probability distribution curves for each crater are shown as colored vertical lines. The horizontal positions of these lines and error bars correspond to their best-estimate ages (see text section 5) and uncertainties listed in table 1. Panel a) shows large impact basins greater than 900 km in diameter. Panel b) shows impact craters <500 km in diameter.

References: [1] Hood, L.L et al (2003), GRL, 30, 6, 1281. [2] Shahnas H. and J. Arkani-Hamed (2007), JGR, 112, E02009 [3] Melosh H. J. (1989), Oxford press. [4] Cisowski S. M. and M. Fuller (1978), JGR, 83, 3441. [5] Quesnel, Y (2009), EPSL277, 184. [6] Ivanov, B. (2001) SSR 96,1,87. [7] Lillis, R ET al. (2010), JGR, 115, E07007. [8] Frey, H.V. (2008), GRL, 35,L13203. [9] Robbins, S. et al. (2013), JGR, in review. [10] Lillis R. et al. (2008), GRL, 35, L14203.