MAGNETIC PROPERTIES OF MARTIAN BASINS COOLED IN A REVERSING DYNAMO. S. C. Steele[1]*, R. R. Fu[1], A. I. Ermakov[2], A. Mittelholz[1], R. J. Lillis[2], R. I. Citron[3], [1]Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138, USA; [2]Space Sciences Laboratory, University of California, Berkeley, Berkeley, CA 94720, USA, [3]MIT/NASA Goddard, Cambridge, MA, 02139 (*sarah_steele@fas.harvard.edu)

Introduction: Although Mars does not currently host a core dynamo, strong crustal fields observed from orbit suggest a dynamo was active in its past [1]. Not all of Mars's crust is strongly magnetized, however; many features including several large, 4.1-3.9 billion-year-old (Ga) impact basins appear completely demagnetized at orbital altitudes. This is often interpreted as evidence that these features formed after (e.g., [2], [3]) or before (e.g. [4]) the martian dynamo shut down. However, the implied ~4.1 Ga dynamo cessation age seems inconsistent with the paleomagnetic record of martian meteorite ALH 84001 [5], [6] and observations of magnetized features requiring an active dynamo at 4.5 and 3.7 Ga [7].

This uncertainty in dynamo cessation age has broad implications for early Mars conditions. Delaying its cessation by hundreds of millions of years could change the timeline of atmospheric escape with important consequences for martian habitability. A later cessation may also constrain the compositions and thermal properties for the martian core and mantle and help constrain possible dynamo mechanisms.

A reversing martian dynamo may reconcile these contradictory estimates of dynamo cessation age. Since large impact basins cool slowly from the surface down, different regions of the impact structure acquire magnetization at different times. Basins cooled in a reversing field can therefore develop regions of oppositely oriented magnetization which could cause them to appear weakly magnetized at altitude [8]. In this framework, young volcanics could appear weakly magnetic either if they cooled quickly or if the mean reversal frequency decreased.

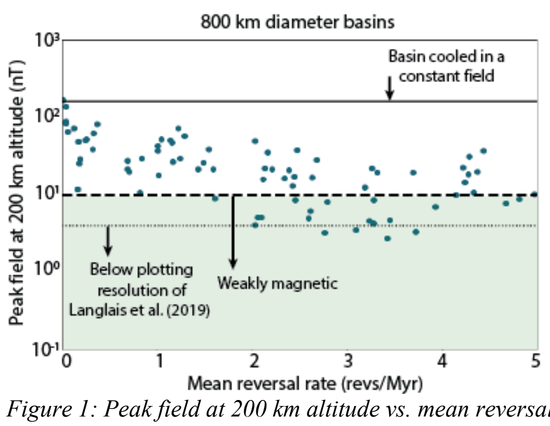

Figure 1: Peak field at 200 km altitude vs. mean reversal rate for 800 km diameter basins. Each point represents the highest field magnitude above the basin for a unique random reversal history. Even basins with peak fields above the plotted thresholds could be considered demagnetized depending on extent of late demagnetization and the strength of nearby crustal fields. For reference, Earth's modern average reversal rate is ~4-5 Myr^{-1}.

Although this idea is promising, it is uncertain if physically plausible reversal rates can quantitatively reproduce the weak observed fields. In this work, we use finite element cooling models to test whether large martian impact basins cooled in a reversing field could appear demagnetized at orbital altitude.

Methods: We computed post-impact thermal profiles in an axisymmetric geometry for 100-1000 km diameter basins by the process defined in Abramov et al. [9] and evolved these using the deal.ii finite element library [10]. Our models included thermal diffusion in the interior and a radiative upper boundary condition. To accommodate rapid early cooling, we used an initial time step of 100 years and increased the time step by 5% at each step. Since Mars's magnetic properties are poorly constrained, we assume the heated material contains equal fractions of magnetite, hematite, and pyrrhotite and has a peak magnetization intensity of 10 A/m.

Each simulated thermal history was combined with a random reversal history to compute the net magnetization at each location within the basin. Random impacts following a crater density distribution for 4.1 Ga surface age [11] were added to simulate remagnetization by subsequent crustal modification within the modelled basin. We then mapped the resulting magnetic field above the basin at 200-km altitude to simulate mapping by spacecraft.

We repeated this process for 80 random reversal histories to characterize the relationship between average reversal rate and peak field strength up to 5 Myr^{-1}. All random reversal histories in this work were generated as Poisson processes.

Results - Influence of reversal rate: From these simulations, we find that peak fields generally increase with basin size and decrease with average reversal rate, as expected (Figure 1). However, random timing of reversals caused modeled peak fields to span about an order of magnitude at any given mean reversal rate.

When reversals were infrequent (<2 Myr^{-1}), peak fields above very large (≥800 km diameter) basins at 200 km altitude typically ranged from 10-100 nT but could be as low as 1 nT. This is well below the >200-300 nT peak fields produced by identical basins cooled in constant fields, suggesting even very slow reversal rates would significantly weaken the magnetic fields produced by large basins. Higher reversal rates (>2 Myr^{-1}) attenuated basin fields even more efficiently, with all peak fields falling between 1 and 30 nT.

Importantly, we find that basins with peak fields below 10 nT occur at all reversal rates between 0.1-6 Myr^{-1}. Because this field value is much lower than the typical crustal fields at 200 km altitude, which range from 30 to several hundred nT [12], these basins would appear demagnetized compared to their surroundings and would therefore be classified as weakly magnetic. Basins meeting this criterion become much more common at reversal rates above ~2 Myr^{-1}.

Results - Influence of shallow, strongly magnetized layer: Another major control on the final magnetic fields above large basins is the formation of a strongly magnetized, near-surface layer. In all basins and for all reversal histories, rapid radiative cooling results in the upper 1-5 km becoming magnetized within a single polarity interval. In contrast, deeper magnetization varies significantly with average reversal rate and specific reversal history. When average reversal rates exceed ~2 Myr^{-1}, the deep interior forms thin layers of alternating polarity that typically sum to undetectable magnetic fields. In this case, the magnetic contribution from the slow-cooling interior becomes less important than that from the much thinner uniformly magnetized surface.

For the largest basins, the field from the near surface alone can be strong enough to cause a basin to appear strongly magnetized regardless of the specific reversal history. However, this shallow magnetization is also susceptible to resetting or removal by impacts, erosion, aqueous alteration, hot ejecta emplacement, and late volcanism. Any demagnetization of the near surface by these or other processes could significantly reduce the field observed at altitude. Whether we ultimately expect basins to appear weakly magnetic at altitude may ultimately depend on the expected extent of near surface remagnetization.

Including just excavation (i.e., neglecting shock and thermal effects) by late impacts, we found that approximately half of 800 km basins would be classified as weakly magnetic if the martian dynamo reversed more rapidly than ~2 Myr^{-1}. Although the specific fraction of weakly magnetic basins is sensitive to assumptions about mineralogy, magnetization depth, and late remagnetization mechanism, this process consistently reduced the fields above large basins by one to two orders of magnitude.

Results - Low altitude field geometry as a recorder of reversal history: Unlike field strength, the field structure at 200 km above large basins exhibits little variation between reversal histories. However, mapping instead at 10 meters above the surface reveals intricate km-scale radial structure that varies with both the characteristic frequency and specific history of reversals (Figure 2). The radial length scale of these field structures increases with the average time between reversals, suggesting low-

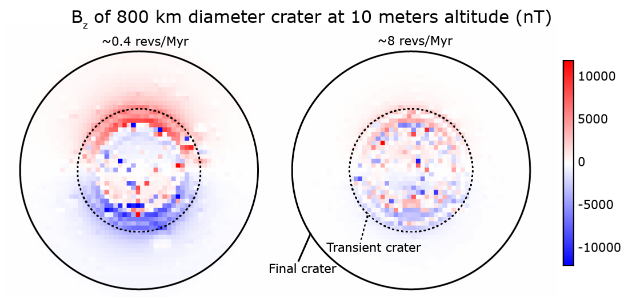

Figure 2: B_z measured at 10 meters above an 800 km-diameter basin for two different average reversal rates. Note that both basins display radial field features at low altitude, but these field structures have longer wavelengths in the basin cooled through less frequent reversals.

altitude magnetic mapping may be useful in constraining the dynamo's reversal rate. No evidence of this small-scale structure persists at orbital altitudes due to resolution limitations but searching for such structure in future mapping at altitudes of tens to thousands of meters may be an effective method of testing whether the martian dynamo was reversing.

Conclusions: We find that a strong but reversing martian dynamo may produce basins that appear weakly magnetized due to resulting regions of oppositely oriented magnetization. However, meeting this condition in multiple basins likely requires reversal rates above ~2 Myr^{-1}, consistent with modern terrestrial rates. At these moderately rapid reversal rates, the magnetic field at altitude is dominated by the contribution of the strong, uniformly magnetized near surface, which is highly susceptible to late alteration and excavation. These results suggest martian reversals at Earth-like rates could explain the observed lack of magnetic field signal above large basins at orbital altitude if near-surface remagnetization is moderately efficient, thereby permitting an active martian dynamo during the formation of large basins.

Low-altitude magnetic measurements can determine whether the martian dynamo was active during large basin formation and place specific constraints on the reversal history. Extending this work to volcanic provinces and the strongly magnetized southern highlands, which cooled very differently from large impact basins, may help further constrain Mars' magnetic history.

References: [1] Acuña, M. H. *et al.* (1999) *Science* 284. [2] Lillis, R. J. *et al.* (2013) *J. Geophys. Res. Planets* 118. [3] Robbins, S. J. *et al.* (2013) *Icarus* 225. [4] Schubert, G. *et al.* (2000) *Nature* 408. [5] Steele, S. *et al.* (in review) *Sci. Adv.* [6] Weiss, B. P. *et al.* (2008) *Geophys. Res. Lett.* 35. [7] Mittelholz, A. *et al.* (2020) *Sci. Adv.* 6. [8] Rochette, P. (2006) *Geophys. Res. Lett.* 33. [9] Abramov, O. & Mojzsis, S. J. (2016) *Earth Planet. Sci. Lett.* 442. [10] Bangerth, W. *et al.* (2007) *ACM Trans. Math. Softw.* 33. [11] Marchi, S. (2021) *Astron. J.* 161. [12] Langlais, B. *et al.* (2019) *J. Geophys. Res. Planets* 124.