COULD WEAKLY MAGNETIZED MARTIAN BASINS REFLECT COOLING IN A REVERSING DYNAMO FIELD? S. C. Steele[1]*, R. R. Fu[1], A. I. Ermakov[2], R. I. Citron[3], R. J. Lillis[2], Z. Levitt[4], [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]Department of Earth and Planetary Sciences, University of California, Davis, Davis, CA 95616, [4]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA (*sarah_steele@fas.harvard.edu)

Introduction: A key unresolved attribute of the extinct martian dynamo is its cessation age. Weak magnetic fields above large ancient impact basins such as Utopia, Hellas, and Isidis have been interpreted as evidence that the martian dynamo shut down 4.1-4.0 billion years ago (Ga) [1–3]. However, a growing body of constraints from remote observations of young volcanic units [4–6] and the paleomagnetism of meteorite ALH 84001 [7, 8] suggests a dynamo cessation after 3.9 Ga. Since the dynamo's cessation may have triggered large-scale climate change on Mars, the difference between these proposed timelines may have important implications for martian habitability.

Although evidence for a post-4.1 Ga dynamo cessation is compelling, a long lifetime must be reconciled with the presence of weakly magnetic 4.1-3.7 Ga basins, which appear inconsistent with formation in strong surface magnetic fields.

Alternatively, these weakly magnetic basins may have cooled in a strong but reversing dynamo field [9]. Because impact basins cool gradually, different sub-volumes heated during the impact cool through the unblocking temperature range of key magnetic minerals at different times. Therefore, if a basin cools in a reversing dynamo field, different layers of material may become magnetized in opposite directions. Since the contributions of these oppositely magnetized layers to the magnetic field at orbital altitudes would partially cancel out, the resulting magnetic field above the basin could be much weaker than that of a basin cooled in a comparable, non-reversing field.

Although this process is conceptually straightforward, it rests on complex interactions between spatially variable basin cooling and stochastic reversal histories. We broadly expect higher reversal rates to be associated with finer-scale magnetization variation and therefore to produce weaker orbital altitude fields. However, it is unclear how sensitive this attenuation is to assumptions about reversal history, basin size, and material properties. In this work, we use a finite element basin cooling model to interrogate these questions and provide a quantitative test of this hypothesis for the formation of weakly magnetic basins.

Methods: We began by calculating axisymmetric post-impact thermal profiles by the analytical process in Abramov et al. [10, 11]. We then simulated the thermal evolution of each basin using axisymmetric finite element simulations built with the deal.ii library [12]. At each grid location, we used the simulated thermal history and a thermal unblocking spectrum inferred from martian meteorites to compute the fraction of magnetization reset at each time step. Assuming a reversal history then allowed us to compute the net fractional magnetization at each location and multiply by a crustal-field-based saturation magnetization intensity to obtain a final magnetization distribution. We then numerically calculated maps of the magnetic field above this distribution at 200-km altitude, simulating magnetic mapping performed by the MAVEN spacecraft.

For each basin size, we computed magnetic field maps for a range of reversal histories. We generated reversal histories as a Poisson process with a range of typical reversal frequencies and mapped them onto time steps in each basin's cooling history. Parameters such as mesh size, model duration, and time step size were varied to accommodate different temporal and spatial scales of cooling for basins of different sizes.

Discussion: We applied 100 random reversal histories to the simulated cooling of eight basins from 100 to 800 km. To study the magnetic signatures of this process, we mapped magnetic fields at MAVEN altitude for each basin size and reversal history combination.

All tested average reversal rates between 0.01-0.25 My^{-1} were capable of producing low (< 10 nT) peak fields above all sizes of basin (Figure 1). We observe a

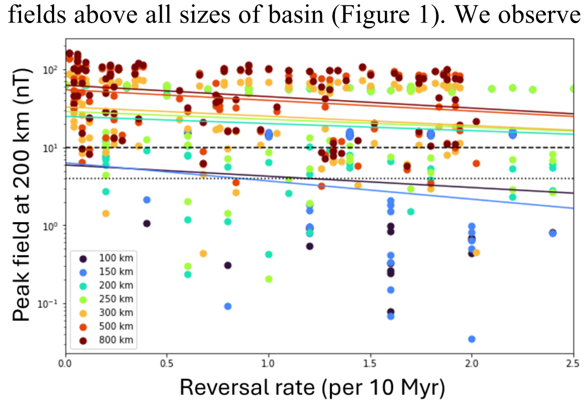

Figure 1: Peak magnetic field at 200 km altitude vs. average reversal rate for all basins. Dashed and dotted lines indicate 10 nT and 4 nT field thresholds, respectively. Colored lines denote best-fit exponentials for each basin size. The "forbidden zone" is compressed by this logarithmic scaling.

wide range of outcomes for each average reversal rate, with peak fields varying by more than an order of magnitude depending on the specific run.

Despite this spread, peak fields trended uniformly lower with increasing reversal rate across all basin sizes (Fig. 1). The relationship between peak field and reversal rate for each basin size can be fitted by an exponential function with similar fitted exponential factors across all basins. This similarity suggests basin size impact's the distribution's shape through its impact on basin cooling timescale, reflecting the first-order dependence of field strength on the number of reversals that occur over the cooling time. For the largest modeled basin, 800 km, this trend predicts that reversal rates of ~1 Myr^{-1}—less frequent, on average, than on Earth—would be required to produce a significant number of basins with peak fields below several nT at 200-km altitude. This suggests physically plausible reversal rates could produce a population of weakly magnetic basins on Mars. Our ongoing simulations will explicitly test this extrapolation by simulating higher reversal rates, which require finer time resolution simulations.

In large basins (≥200 km) we also observed the development of a high field "forbidden zone" at higher reversal rates. This suggests that more rapid reversals may impose a stricter limit on peak field strength.

Field structure. We found that field morphology may also play an important role in the detectability of basin fields. At higher reversal rates, the magnetization distributions that developed within the basins were more complex. These yielded highly structured magnetic fields immediately above the basin (Fig. 2A) that partially cancelled at altitude to produce extremely weak fields in the basin's center (Fig. 2D). The peak fields for these basins occurred at the edges, where they could be most efficiently masked by Mars' heterogeneous background fields. Even basins in our simulations that are theoretically detectable by MAVEN might be mistakenly classified as demagnetized if their peak fields were attributed to other source regions.

Ongoing work. We intend to build on this work in several important ways. First, we will extend this analysis to larger basins using post-impact thermal profiles obtained from hydrocode simulations. We will also incorporate heterogeneous background magnetizations into these models. Finally, we will extend this study to higher reversal rates to directly test our predictions from this work.

While these results show that large weakly magnetic martian basins may have formed in a reversing dynamo, they may also provide several pathways to constraining a possible martian reversal history. First, if magnetization has been well-preserved, mapping of basin fields at lower altitudes may reveal axisymmetric

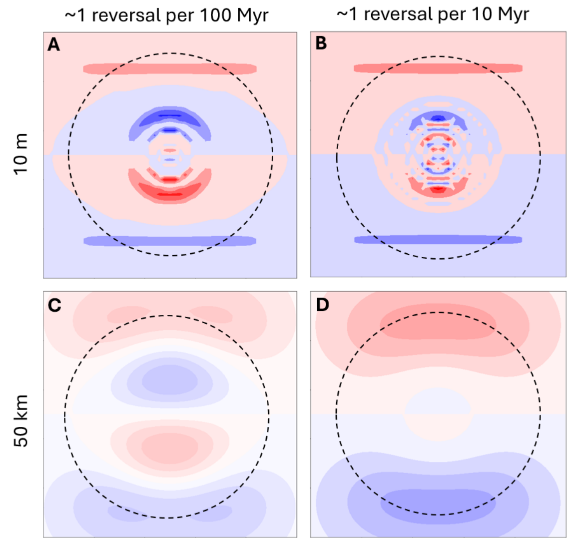

Figure 2: Maps of vertical magnetic field component computed at 10 m (top) and 50 km (bottom) of 500 km basins cooled through two different average reversal frequencies. At higher reversal rates, a region of weak field can develop in the basin's center at altitude.

field morphology characteristic of cooling through reversals (e.g. Figure 2). Mapping fields above a larger population of real basins may also permit useful statistical tests. If reversals did occur, it may be possible to extract their average frequency by identifying a high field "forbidden zone" in this population. An average reversal rate could also be estimated by analyzing the magnetic fields of smaller basins; although magnetic fields above large basins are better characterized, their relative rarity and long cooling timescales may make them less suited to distinguishing between a reversing dynamo and a short-lived one.

Conclusions: We simulated basin cooling in reversing fields to test whether this process could produce the weak magnetic fields measured over some large martian basins. Although all reversal rates tested were capable of producing weak basin fields, average reversal rates ~1 Myr^{-1} would be required to produce a significant number of basins with peak fields undetectable by MAVEN. Even slower reversal rates may also be possible if heterogeneous background fields efficiently mask fields near the basin edges. This suggests that the absence of fields above some impact basins does not preclude the presence of a strong martian dynamo.

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