EVIDENCE FOR A LONG-LIVED, POTENTIALLY REVERSING MARTIAN DYNAMO. S. C. Steele1*, A. Mittelholz2, R. R. Fu1, R. J. Lillis3. 1Harvard University, MA, USA; 2ETH Zurich, Switzerland; 3Space Sciences Laboratory, University of California, Berkeley, CA, USA (sarah_steele@fas.harvard.edu).

Introduction: Although Mars’s strong crustal fields suggest the planet hosted a core dynamo early in its history [1], the dynamo’s strength, direction, and morphology through time are poorly known.

Mars’s early magnetic field is of broad interest in part because it may have been integral to the planet’s climatic evolution. Depending on the field’s strength and geometry, interactions between the global magnetic field and the solar wind may have either reduced or enhanced atmospheric loss [2,3]. Magnetically-mediated ion escape could be particularly important for O+ and other heavy ions which do not experience efficient thermal escape [e.g. 2-4].

Additionally, the duration and style of dynamo generation depend on the thermal properties and initial temperature of Mars’s core. Properties of the early dynamo, and in particular its cessation age, may therefore provide insight into Mars’s deep interior [5].

It has been argued that Mars’s dynamo shut down at ~4.1-4.0 Ga to accommodate the very weak magnetic fields associated with most large Martian impact basins [6,7]. This reflects the assumption that the large volumes of material heated during basin formation should have acquired a strong, uniform magnetization if the dynamo was active; if this were the case, we would expect the magnetic fields above large basins to be much stronger than observed [8]. However, observations of younger magnetized volcanics edifices seem to require an dynamo that was active until 3.9-3.6 Ga [e.g. 9].

Since Mars 9th, we have used a combination of meteorite paleomagnetism, modeled magnetization of large impact basins, and statistical analysis of Martian crustal fields to further constrain Mars’s magnetic history. Our results suggest that 1) the Martian dynamo was likely active until at least ~3.9 Ga and potentially reversing, and 2) weakly magnetic impact basins do not necessarily imply an early dynamo cessation.

ALH 84001 Paleomagnetism: First, we revisited the paleomagnetic record of the Martian meteorite ALH 84001 using the high-resolution magnetic imaging capabilities of the quantum diamond microscope (QDM). We found that primary igneous chromite-sulfide assemblages in the sample host two nearly antipodal magnetization directions. Both populations were magnetized in strong fields, with estimated paleointensities of 42 ± 20 μT and 15 ± 11 μT, respectively. This unique pattern of strong magnetization requires an active dynamo until at least ~3.9 Ga and suggests it may have experienced polarity reversals, in agreement with findings from crustal field inversion studies [10].

Magnetism of Large Impact Basins: Although ALH 84001 paleomagnetism and observed young magnetized volcanic features [e.g. 9] both support a long-lived dynamo, this must be reconciled with the observed weak magnetic fields above large Martian impact basins. We identified two processes which could cause impact basins that formed while the dynamo was active to be less magnetic than expected. First, since crustal material may be enriched in magnetic minerals compared to the Martian mantle, as is the case on Earth [11], excavation during basin formation may significantly reduce the magnetic fields above large basins [12]. Second, since basins cool over 100 Myr timescales, magnetic polarity reversals may create layers magnetized in opposite directions which partially cancel to produce small net fields at high altitude [13,14].

By comparing the magnetic fields observed above Martian craters with those above other Martian crust, we found that most craters with diameters >150 km were statistically likely to be associated with magnetic lows [12]. This result is consistent with the hypothesis that excavation may play an important role in making impact basins appear weakly magnetic [9].

Next, we used finite-element cooling simulations to model acquisition of magnetization in basins with diameters of 200-1800 km. We paired these cooling models with a range of random reversal histories to characterize the relationship between mean reversal frequency and the magnetic field at both ~10 km altitude and spacecraft orbital altitude of 200 km. We found that a Martian dynamo reversing at Earth-like rates could reduce the expected magnetic field strengths above large basins by an order of magnitude or more (e.g. Fig. 1) [14].

Whether reversals are necessary to reproduce the <5 nT field strengths at 200 km altitude above Mars’s large basins ultimately depends on the magnetic properties of the material remaining after the impact. If saturation magnetization intensities were <0.25 A/m, excavation alone would be sufficient for all large impact basins on Mars to appear weakly magnetic at 200 km altitude. A dynamo reversing at an average frequency ≥1.5 Myr⁻¹ could permit saturation magnetization intensities as high as ~5 A/m while still producing basins with undetectable magnetic fields at orbital altitudes. This intensity is greater than the median value for Martian meteorites assuming a ~50 μT paleofield [15].

Given the sensitivity of these results to the magnetic properties of Mars’s crust and mantle, this remains a core question. Preliminary work to characterize expected igneous magnetic mineralologies of Martian
mantle material suggests saturation magnetization intensities of ~0.05-2 A/m [16].

Fig. 1: Simulated maps of an 800 km diameter basin for a non-reversing field (left), a typical slow reversal history (center), and a typical fast reversal history (right). Plots show (A) Bz at 200 km altitude, (B) Bz at 10 km altitude, and (C) a profile of the net magnetization beneath the basin along a transect from the basin’s center to its final radius. The dashed and dotted circles in panels (A) and (B) indicate the transient and final basin diameters. Even infrequent reversals significantly reduce basin field strengths, with rapid reversals reducing them even further. High-altitude field morphologies are generally dipolar, but complex field structures emerge at lower altitudes.

These results imply that satellite magnetic field measurements alone cannot determine whether basins were formed in a reversing dynamo or after the dynamo’s cessation. A inactive dynamo is therefore not required during the formation of Mars’s large impact basins, thereby removing the strongest argument in favor of a dynamo cessation at 4.1-4.0 Ga.

Importantly, we found that reversals produce alternating striping in the magnetic field at lower altitudes (e.g. Fig. 1B). The horizontal length scale of these structures increases with the average time between reversals, suggesting magnetic mapping at or below 10 km altitude may be useful in determine whether, and how often, the Martian dynamo was reversing [14]. However, relatively long transsects (~100 km) would be required.

Implications of a Long-Lived Dynamo: A dynamo persisting until 3.9-3.6 Ga would require long-lived convection in Mars’s core. It is uncertain whether core crystallization could have powered a longer-lived dynamo; although inferences of a large core with a high light element content would be incompatible with a solid inner core [17], this argument is weakened by recent detections of a basal “mushy” layer, which may permit a smaller core with lower a light element content [18,19]. However, recent experiments suggest a low thermal conductivity for the Martian core, potentially permitting a long-lived dynamo that was completely thermally driven [20].

A dynamo active until 3.9-3.6 Ga would also have different implications for atmospheric escape. A Martian dynamo consistent with paleointensities recovered from ALH 84001 [10] could decrease ion loss by a factor of a few under early solar system conditions [3], potentially preventing the escape of O equivalent to a ~1-10 m global equivalent layer of water before the end of the Noachian. This is consistent with evidence for valley network formation persisting until 3.5 Ga or later [21].

Outlook: This work has several important implications for the Mars research and the future Mars program. First, high-resolution magnetic imaging may continue to play a key role in the study of Martian magnetism. The same magnetic imaging techniques used to characterize magnetization in ALH 84001 may be applied to characterize magnetization in returned samples. Ongoing experiments to characterize the magnetic response of Martian materials to high pressures using a hybrid QDM-diamond anvil cell may also be valuable for interpreting both meteorite and crustal magnetism [22].

Additionally, our results suggest low-altitude magnetic mapping of impact basins with helicopters or balloons could help address many of the remaining questions in Martian magnetism [23], including whether, and how frequently, Mars’s dynamo reversed [14].

Finally, a better understanding of the expected magnetic mineralogies of Martian materials, including the effects of exsolution and alteration, will be essential for accurate interpretation of Mars’s crustal magnetism moving forward.