IDENTIFICATION OF MAGNETIC PHASES BY PERSEVERANCE AND IMPLICATIONS FOR PALEOMAGNETIC ANALYSIS OF RETURNED SAMPLES. E. N. Mansbach[1], T. V. Kizovski[2], L. Mandon[3], E. L. Scheller[1], T. Bosak[1], R.C. Weins[4], C. D. K. Herd[5], B. P. Weiss[1], [1]Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, [2]Brock University, Toronto, Canada, [3]California Institute of Technology, Pasadena, CA, USA, [4]Los Alamos National Laboratory, Los Alamos, NM, USA, [5]University of Alberta, Edmonton, Canada.

Introduction: Mars does not have an internally generated magnetic field today, but the identification of remanent magnetization in the crust [1] and in Martian meteorites [2, 3] indicates Mars once possessed a dynamo. However, the lifetime of the dynamo is uncertain: current estimates from crustal anomalies suggest 4.5-3.7 Ga [4]. Determining the time when the dynamo was active is vital to understanding the evolution of the Martian interior and habitability: the thermochemical history of the core, if Mars possessed plate tectonics, and the role of the dynamo in the loss of the early Martian atmosphere and surface water [5].

The Perseverance rover is currently exploring a delta in the Jezero impact crater at the edge of the Isidis basin [6]. The delta is emplaced on top of the crater floor, which consists of an olivine cumulate (Séitah formation) overlain by basalt (Máaz formation) [7]. Delta exploration thus far has revealed units consisting of sand-sized and sand-to-silt-sized grains, with some units containing abundant sulfate minerals [8].

A key goal of the mission is to collect samples for future return to Earth. Unlike Martian meteorites, these samples will have known geologic contexts, are almost all oriented samples of bedrock, and will not have been exposed to weathering on Earth. Perhaps most importantly for this study, the samples are expected to range in age from ~2 to >4 Ga [6] and so may record the early history and later demise of the dynamo. To understand the paleomagnetic record of the future returned samples, we will need to determine their ferromagnetic mineralogy, the grain sizes, and how they became magnetized. While magnetic phases that formed during the cooling of igneous rocks would retain a thermoremanent magnetization (TRM), subsequent aqueous alteration could lead to a chemical remanent magnetization (CRM). Grains transported and deposited in the delta could also record a detrital remanent magnetization (DRM) during settling in water.

Here, we synthesize past and report new observations of potential ferromagnetic phases from the Planetary Instrument for X-Ray Lithology (PIXL) [9] and SuperCam (SCAM) [10] instruments. Coupling the observations with geologic context, we provide a first look at what magnetic phases exist in the samples, the magnetizations the phases are likely to retain, and implications for future analysis of the returned samples.

Identifying iron oxides: Based on previous studies of Martian meteorites (e.g., [2]) and data from past missions like Spirit and Curiosity (e.g., [11]), phases that may be in the samples and are ferromagnetic at room temperature include magnetite (Fe_3O_4), titanomagnetite [$Fe_{3-x}Ti_xO_4$ with $x < 0.8$], maghemite (γ-Fe_2O_3), hematite (α-Fe_2O_3), titanohematite [$Fe_{2-x}Ti_xO_3$ with $x < 0.8$], pyrrhotite ($Fe_{0.8-1}S$), and goethite [FeO(OH)]. Since iron oxides can be difficult to identify unambiguously in rover data, we use multiple lines of evidence to infer if and where these phases are present.

PIXL uses X-ray fluorescence (XRF) to create high-resolution elemental maps and identify regions enriched in elements often found in magnetic phases (Fe, Ti, Cr). However, the 0.125 mm PIXL spot size means that signals from multiple grains are likely sampled at each location. PIXL cannot constrain iron oxidation states.

SCAM measures elemental compositions using laser induced breakdown spectroscopy (LIBS) and can collect visible and near-infrared spectra (VISIR) to identify mineralogy. The 0.2 – 0.4 mm diameter LIBS spots likely contain signals from multiple grains. VISIR spectra can assist in diagnosing iron oxidation state and identifying iron oxides and oxyhydroxides [10].

Reports of iron oxides:

Crater Floor: PIXL scans of a Séitah abrasion patch (Fig. 1A) show regions enriched in Fe, Ti, and Cr [12]. The Fe- and Cr-enriched areas are collocated with olivine and pyroxene while the Fe- and Ti-enriched regions occur in the surrounding mesostasis. Due to grain signal mixing, we cannot determine the stoichiometry of the iron oxides. However, since the Cr-enriched areas can contain up to 19.1 wt.% Cr, these grains may be chromite ($FeCr_2O_4$) or Cr-substituted titanomagnetite, both of which are not ferromagnetic at room temperatures (although nonstoichiometric Cr and Ti spinels may be ferromagnetic [2]). The Ti-enriched oxides in the mesostasis are likely titanomagnetite or ilmenite [$FeTiO_3$, not ferromagnetic] based on their Ti/Fe ratios. VISIR spectra indicate the presence of alteration phases such as nonferromagnetic ferrihydrite [$Fe_{10}O_{14}(OH)_2$] [13], while normative mineral compositions derived from LIBS imply 1.6 wt% magnetite and 1.1 wt% ilmenite in the formation [14].

The PIXL data from an abrasion patch in the Máaz formation shows no Cr-enriched oxides (Fig. 1B). However, there are twice the number of locations enriched in Fe and Ti compared to the Seitah abrasion patch. These areas are indicative of titanomagnetite or ilmenite. CIPW compositions from LIBS data imply 1.8

wt% magnetite and 0.4 wt% ilmenite [14]. VISIR spectra suggest the presence of iron oxyhydroxides [13].

Delta Front: Only one spot in the Thorton Gap abrasion patch [Skinner Ridge sandstone, Fig. 1C] exhibits enrichment in Fe, Ti, and Cr and therefore may be a Cr-rich titanomagnetite. VISIR spectra on abrasion patches in the Amalik and Devils Tanyard members suggest the presence of magnetite and hematite [15].

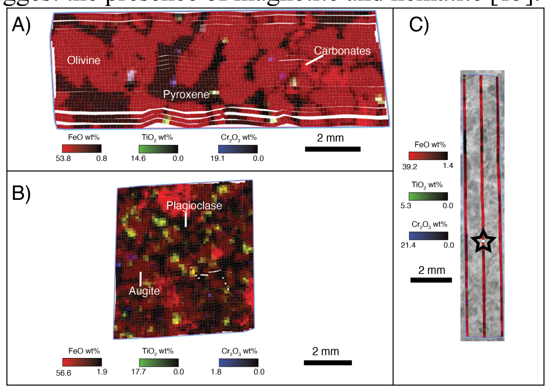

Figure 1: (A) PIXL map of the Dourbes (Séitah) abrasion patch (B) PIXL map of the Guillaumes (Máaz) abrasion patch (C) PIXL line scan of the Thorton Gap (Skinner Ridge) abrasion patch with context image. Yellow/green spots are Fe-Ti oxides, white spots are Fe-Ti-Cr oxides, and blue/purple spots are Cr-rich oxides. The star in C) shows the one detection of an iron oxide.

Acquisition of magnetic remanence: The igneous textures of the Séitah and Máaz units and the primary nature of the mafic silicates suggest that titanomagnetite, if present, would have acquired a TRM during primary cooling. SHERLOC and SCAM data indicate that fluids have partially altered both units [14, 16], but future analyses on Earth will be needed to determine if that alteration has led to the formation of a secondary CRM. If magnetite is present in Máaz and Séitah at 1-2 wt%, which is comparable to Earth basalts, the magnetization of the returned samples (~1×10^{-8} Am^2 for a 1 mm^3 subsample) should be easily measurable by a superconducting rock magnetometer (noise floor ~1×10^{-12} Am^2).

Further analyses are needed to detect iron oxides in the delta. The potential titanomagnetite found at Skinner Ridge has an uncertain remanence acquisition method. If the grain is detrital, it may carry a TRM acquired during its initial cooling in the Jezero watershed (> 4 Ga). The average size of the grains in the abrasion patch (~250 µm) also indicates that if a field was present, the grain could have acquired a DRM during its deposition (3.8 – 3.6 Ga) [17, 18]. As this timeframe spans the current youngest evidence for a dynamo [4], these samples and future, younger delta samples could aid in constraining the time of dynamo cessation.

Alternatively, if the grain formed during aqueous alteration, it may have acquired a grain-growth CRM as the mineral passed through its blocking volume. In this case, the timing of the dynamo field could be constrained to when the diagenesis occurred. The cross-cutting relationships of the potential magnetite and hematite grains in Amalik and Devils Tanyard with their host rocks are currently uncertain. Sample return should determine if these phases formed as a result of alteration processes or prior to deposition.

Séitah is the lowest lying unit encountered by the rover thus far, so its magnetic phases would retain the oldest non-detrital magnetic record. However, the ~3.8 Ga age of the unit [19] is older than the youngest evidence for a dynamo [4]. Therefore, these samples would not constrain the age of dynamo cessation, but could perhaps provide the field intensity and direction during the period when dynamo decayed.

Conclusion: The identification of iron oxides in multiple formations studied by Perseverance indicates that the returned samples will provide numerous opportunities to study the characteristics of the Martian dynamo and its decay. Samples that record a TRM will allow us to measure an absolute paleointensity while samples that have DRMs, which are acquired continuously, could look for evidence of true polar wander and plate tectonics. Looking forward, the rover will eventually drive outside of the crater and encounter rocks that could have formed prior to the impacts that created the Jezero crater and Isidis basin (~4 Ga). Collecting samples that formed prior to 4 Ga, when the meteorite ALH 84001 acquired its remanence [2], provides a higher chance of measuring the ancient field and therefore more opportunities to study the properties of the dynamo. Together, future and already cored samples from Perseverance promise to reconstruct the most detailed history of Martian dynamo yet.

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