MARTIAN CHRONOLOGY AND MARS SAMPLE RETURN.

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Introduction: Martian meteorites have provided a timescale for Mars' magmatic evolution, including evidence for early accretion and core formation within ~10 million years of Solar System formation, and magma ocean differentiation and formation of meteorite source regions all before ~4.5 billion years ago (e.g., [1-3]). The crystallization ages of the meteorites themselves provide evidence for volcano-magmatic processes on Mars, and evidence for metamorphic and alteration events are also recorded within some meteorites [4,5]. Along with crater counting chronology [6] and some *in-situ* ages obtained from the Curiosity Rover [7], these data form our current understanding of martian history. MSR at Jezero Crater promises to greatly expand this understanding through precise radiometric age dates obtained within terrestrial laboratories on a range of possible rock types and their components. It should also reduce the uncertainties currently inherent in crater counting chronology and provide a time framework for fluvial processes and possible life-sustaining conditions on Mars.

Meteorite chronology: Martian meteorite types span from the dominantly basaltic breccia NWA 7034 and its pairs that has components that crystallized in the Noachian (4.34 Ga [8]), along with orthopyroxenite ALH 84001 (~4.1 Ga [9]) (**Fig. 1**). The entirety of the Hesperian period of Mars is unsampled by meteorites, with the first Amazonian aged rocks being two augite-rich basaltic meteorites (NWA 7635/8159; ~2.4 Ga [10,11]). Many nakhlite and chassignite meteorites form the most coherent suite of rocks from Mars (~1.34 Ga [12]), with the most abundant martian meteorites being shergottites that come from a range of long-lived incompatible element enriched, intermediate and depleted sources (0.15-0.7 Ga, e.g., [5]). Within the meteorites themselves lie both relative and absolute chronological evidence for significant metamorphic (e.g., NWA 7034+), and alteration events.

Some uncertainty has arisen regarding shergottite crystallization ages from Pb isotope data for bulk rocks and their components suggesting possible 'isochron' ages as old 4.1 to 4.3 Ga [13]. These apparent ages, however, do not match a range of other radiometric dating systems (K-Ar, Rb-Sr, Sm-Nd, Lu-Hf, Re-Os, Pb-Pb dating of phosphates and baddeleyite), and it has been postulated that the ancient Pb ages reflect mixing or contamination by terrestrial, or even martian materials [14]. MSR will certainly help to address this issue.

***In-situ* dates at Gale Crater:** A few *in-situ* ages have been made using instruments on the Curiosity Rover at Gale Crater. From the bottom to the top of the studied Bradbury Fm., and including only what are considered robust ages, these are 4.2±0.4 Ga (Cumberland) and 4.1±0.6 Ga age (Mojave 2), with a 2.1±0.4 Ga for jarosite in the Murray Fm. [7]. The more ancient ages are from detrital minerals of precursor basaltic material (plagioclase, pyroxene) and are older than the 3.5 to 3 Ga estimated ages of sedimentary activity at Gale Crater [15].

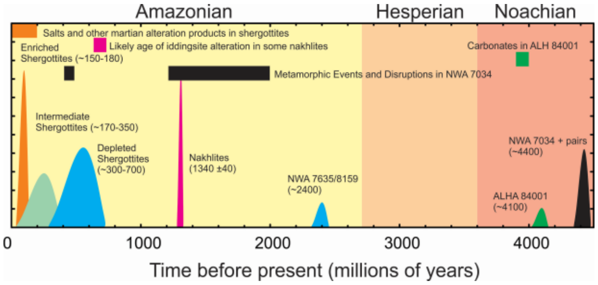

Figure 1: *Summary of martian meteorite chronology, showing crystallization ages as approximate density functions and post-crystallization processes as bars. Data sources are noted in the text. Ages shown in parentheses are in Ga.*

Crater counting chronology and possible meteorite source craters: The primary means for understanding martian surface ages comes from measuring the spatial density of craters and is calibrated to absolute radiometric ages from Apollo and Luna mission samples that were used to produce this timescale for the Moon (e.g., [6]). Currently, vast periods of time in the crater counting chronology are uncalibrated with radiometric ages, from 4.5-4.0, 3-0.8 and 0.8-0.2 billion years ago (see Fig. 2 of [6]), resulting in extrapolations that can lead to >1 Ga uncertainties on surface ages. This uncertainty is compounded by correct identification or primary impact craters as well as the ability to properly count and interpret small craters, 1 km or less in diameter [6]. Consequently, crater spatial density analyses for martian surfaces cannot currently be considered precise in most instances. This issue, combined with difficulty in matching compositions of craters obtained by spectral reflectance data, has made identifying martian meteorite source craters challenging, with no source crater positively identified to date, but with many candidate craters suggested. With respect to crater spatial densities, and ground truth for spectral reflectance, MSR has the potential to revolutionize our understanding. In particular, the Jezero Crater landing site selected for the Perseverance Rover and MSR will likely be a treasure-trove for examining the timescales of processes both within and on Mars.

Current chronology at Jezero Crater: Jezero Crater, lying at the edge of the ~3.96 Ga Isidis Planitia basin and on the margins of the Noachian Nili Fossae terrain and Hesperian Syrtis Major volcanic region, is the selected target site for the Perseverance Rover and MSR (**Fig. 2**). Jezero crater is an attractive location for MSR, potentially enabling sampling of a range of materials, including pre-Isidis basin materials, impact ejecta, volcanic materials from within the interior of Jezero Crater and, critically, fluvial deltaic sediments from a catchment area including olivine-rich material from Nili Fossae and possibly from Syrtis Major. The evidence for fluvial activity over a prolonged period means that Jezero Crater may also be a location where biotic processes were sustainable on Mars and a chronological framework for understanding this evidence will be critical (**Fig. 3**).

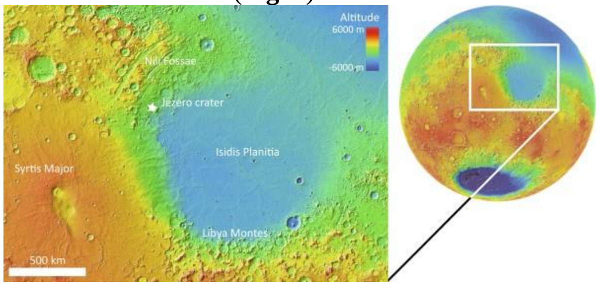

Figure 2: *Location of the Jezero Crater on Mars, showing major reginal features. Image from [16].*

The Jezero crater landing site will provide some critical calibration for chronology from crater counting as well as a range of other processes via MSR. This will include sampling the dark toned deposit, interpreted as a pyroxene-rich lava flow that has been variably dated at 3.5 to 1.6 Ga ([17-19]). Another potential calibration point would be from detrital materials from the Nili Fossae Olivine Rich Unit, dated at ~3.8 Ga from crater densities [16]. The proposed traverse made by the Perseverance rover has the potential to sample detrital grains and washed in material to the crater from multiple terrains.

Meteorite chronology between now and MSR: A significant fraction of martian meteorites (>50%) do not have crystallization ages. Measuring ages in these samples, including post-crystallization age information will be critical to providing a stronger framework for martian meteorites, but also for fine-tuning techniques to be used for MSR. Further efforts to identify likely sources of meteorites will also be important for placing these rocks into context, such as possible rejuvenated volcanism origins for nakhlites and chassignites [20].

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References: [1] Dauphas, N., Pormand, A., 2011 *Nature* **473**, 489-492; [2] Borg, L et al. 2016 *GCA* **175**, 150-167; [3] Kruijer, T et al. 2017 *EPSL* **474**, 345-354; [4] Borg, L., Drake, M., 2005 *JGR* **110**, 1-10; [5] Vaci, Z., Agee, C., 2020 *Geosci*. **10**, 455; [6] Robbins, S. 2014 *EPSL* **403**, 188-198; [7] Cohen, B. et al. 2019 *Astrobio.* **19**, 11; [8] Bouvier, L. et al. 2018 *Nature* **558**, 586-589; [9] Lapen, T. et al. 2010 *Science* **328**, 347-351; [10] Lapen, T. et al. 2017 *Sci. Adv*. **3**, 1-7; [11] Herd, C. et al. 2017 *GCA* **218**, 1-26; [12] Udry, A., Day, J. 2018 *GCA* **238**, 292-315; [13] Bouvier, A. et al. 2009 *EPSL* **280**, 285-295; [14] Borg, L. et al. 2016 *GCA* **175**, 150-167; [15] Grotzinger, J. et al. *Science* **350**; [16] Mandon, L. et al. 2020 *Icarus* **336**, 113436; [17] Schon, S et al. 2012 *PSS* **67**, 28-45; [18] Goudge, T. et al. *JGR* **117**, E00J21; [19] Shahrzad, S. et al. 2018. *GRL* **46**, 24082416; [20] Day, J. et al. 2018, *Nat Comm.* **9**, 4799.

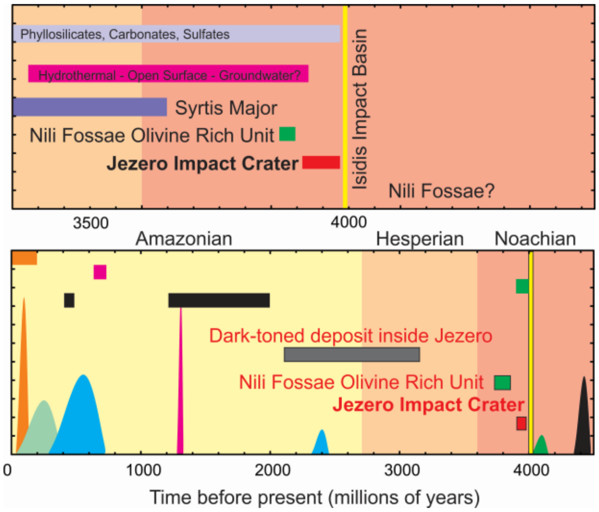

Figure 3*: Current chronology of events and units within the region of Jezero Crater shown relative to martian meteorite chronology from Fig. 1. Data sources provided in the text.*

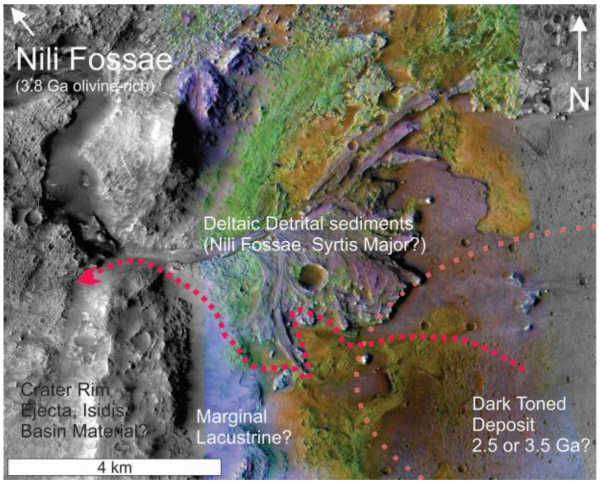

Figure 4: *NASA MRO image of western margin of Jezero crater, with annotation, landing site ellipse (pink) and possible traverse of the Perseverance Rover (red).*