WHAT HAVE WE LEARNED ABOUT THE INTERIOR AND SURFACE OF MARS FROM MARTIAN METEORITES. A. Udry[1], G. H. Howarth[2], C. D. K. Herd[3], J. M. D. Day[4], T. J. Lapen[5], J. Filiberto[6], and A. M. Ostwald[1] [1]Department of Geosciences, University of Nevada Las Vegas, 4505 S. Maryland Pkwy, Las Vegas, NV 890154 (arya.udry@unlv.edu), [2]Department of Geological Sciences, University of Cape Town, Rondebosch 7701, South Africa, [3]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, T6G 2E3, [4]Scripps Institution of Oceanography, University of California San Diego, La Jolla CA 92093-0244. [5]Department of Earth and Atmospheric Sciences, University of Houston, Houston TX 77204, [6]Lunar and Planetary Institute, USRA, Houston, TX 77058.

Diversity of martian samples: Martian meteorites are the only samples currently available from Mars, before samples will be returned to Earth in 2031 by the Mars Sample Return (MSR) campaign. Samples are necessary to better constrain geological processes, including emplacement of magmatic rocks, geochemical diversity of the martian interior (crust and mantle), abundances and distribution of volatiles, planetary accretion and differentiation, bulk Mars composition, and secondary processes, such as alteration. Here we review the main discoveries from martian meteorites, focusing on the past six years [1].

There are currently 262 officially classified martian meteorites, likely representing 150 pairing groups (Fig. 1, Meteoritical Bulletin Database). The rate of recovery of these meteorites has increased since 2014, with 73 meteorites recovered, which include samples with diverse textures, mineralogies, and bulk compositions [1]. Martian meteorites have mafic to ultramafic bulk compositions and are divided into three main groups: 1) Shergottites, the main group of martian meteorites (2403–150 Ma old intrusive and extrusive basaltic rocks consisting of pyroxene and plagioclase/maskelynite with variable olivine abundances). The shergottite group includes the only early Amazonian (~2.4 Ga) augite-rich specimens, Northwest Africa (NWA) 8159 and NWA 7635 [2,3], which are distinct in mineralogy and ages from the other shergottites; 2) Nakhlites (~1.3 Ga old clinopyroxene-rich cumulates with olivine), and 3) Chassignites (~1.3 Ga dunites), as well as two individual Noachian rocks: Allan Hills (ALH) 84001 (~4.1 Ga old orthopyroxenite) and NWA 7034 and its 16 paired meteorites, the only martian sedimentary sample (a polymict regolith breccia with up to 4.5 Ga igneous clasts) [1,4,5].

Secondary processes: Martian meteorites record secondary processes, such as terrestrial alteration and shock metamorphism in addition to magmatic and martian alteration processes [1]. Terrestrial alteration is common in martian meteorites because the large majority are finds, and is represented mostly by presence of carbonates, evaporites, and an observed light rare earth element (LREE) enrichment of the bulk composition. Shock metamorphism occurs when martian samples are ejected from the surface from impact, with martian samples having undergone shock pressures from 5 GPa (nakhlites) up to 70–90 GPa (shergottites) [6,7].

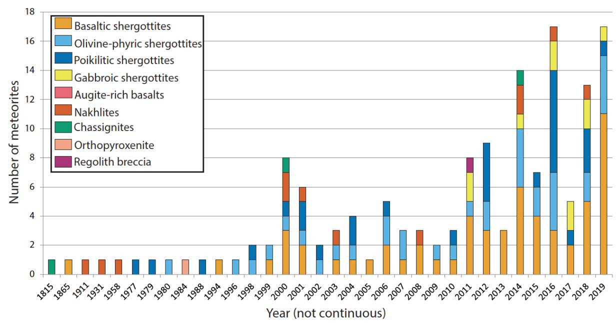

Fig. 1. Number of meteorites recovered each year separated by types of martian meteorites (no continuous years).

Alteration surface processes: Martian alteration, as evidenced by hydrous minerals, which are found in martian meteorites, can help us better understand the hydrological cycle on Mars. All martian meteorites show alteration minerals, with various abundances, including iddingsite, phyllosilicates, evaporites, pyrite, and carbonates. Nakhlites generally exhibit the highest amount of alteration [1] and is perhaps related to a hydrous alteration event at ~633 Ma, possibly aided by shock brecciation [8]. Pyrite found in NWA 7034 likely represents hydrothermal activity [9]

Igneous emplacement of martian magmas: Textures and mineralogies of martian meteorites suggest diverse emplacement processes in the martian crust. Shergottites are divided into four different sub-types according to their textures, bulk chemistry, and mineralogy, including basaltic, olivine-phyric, poikilitic, and gabbroic. These sub-types likely originate from the same magmatic systems or bodies [10, 11]. However, we do not see correlation between sub-types, sources, and ages, possibly due to the fact that we have a biased sampling of shergottites [1]. Nakhlites and chassignites likely formed in the same magmatic body, but as various flows and/or sills [e.g., 12]. Nakhlites and chassignites originate from the same mantle source. It was suggested by [13] that nakhlites are linked to shergottite-like magmas, with shergottites representing main shield and nakhlites representing rejuvenated magma, in a stagnant-lid regime.

A poorly mixed martian interior: The martian mantle is heterogenous in respect to trace elements and isotopic compositions, including Rb-Sr and Sm-Nd systems (Fig. 2) [1]. These heterogeneities have been formed early during differentiation of Mars, associated with martian magma ocean solidification and overturn likely 20–100 Myr after formation of Calcium Aluminum Inclusions (CAIs) [see 1 and references therein]. A minimum of six mantle reservoirs are present in the martian mantle: a mixture of three for shergottites and ALH 84001 [3,14], one for nakhlites and chassignites [15], perhaps one for NWA 8159 [16], and at least one for NWA 7034 [17]. Zircons in NWA 7034 igneous clasts shows that a possibly crustal, enriched source, distinct from the enriched shergottite source was present during early Mars [5].

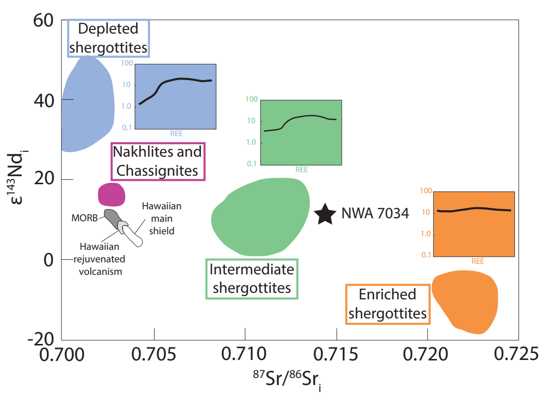

Fig. 2. Different shergottite, nakhlite, chassignite, and NWA 7034 sources based on initial $\varepsilon^{143}Nd_i$ and $^{87}Sr/^{86}Sr_i$ bulk compositions, and, in the case of shergottites, level of Light Rare Earth Element (LREE) enrichment (modified after [13, 18]; NWA 7034 data from [4].

Volatiles on Mars: The abundance of magmatic volatiles through time is still debated: Are martian magmas drier than terrestrial magmas or were magmas hydrous with degassing of volatiles before eruption? [19]. Analyses of hydrous (apatite, amphibole) minerals, melt inclusions, anhydrous minerals, and impact melts can help us constrain the volatile content of the martian interior. McCubbin et al. [9] have determined that 36–73 ppm and 14–23 ppm correspond to the water content of the enriched and depleted shergottite sources, respectively. Furthermore, the bulk martian crust D/H remained the same for >3.9 Ga [20].

Where do they come from? One major unknown regarding martian meteorites is their location of origin on the martian surface. Martian meteorites originate from at least 11 ejection sites according to their cosmic-ray ejection ages, ejected between 0.7 and 20 Ma. Two large groups of martian meteorites originate from the same location: Nakhlites and chassignites all likely come from the same location with ejection age of ~10.7 ± 0.8 Ma [21], and most depleted shergottites (>20) were ejected at ~1.1 ± 0.2 Ma [3]. To define crater sources for meteorites, various characteristics have to be taken in account, including ejection and crystallization ages, mineralogy, and geologic context. Crater sources have been suggested for some meteorites but none have been definite [22, 23], as not all of the characteristics are consistent with those of meteorites. Better calibration is needed to constrain source craters.

What does this mean for returned samples? Meteorites are biased samples of the martian crust. Only two samples (ALH 84001 and NWA 7034) are Noachian, whereas >50% of the martian surface is Noachian. In addition, alkaline and felsic rocks (> 55 wt.%) have been analyzed at the martian surface by the *Spirit* and *Curiosity* rovers [24,25]. However, only rare evolved compositions were found in martian meteorites. We also cannot constrain the geologic field context of martian meteorites. The Mars 2020 mission, which will land in Jezero crater February 18th 2021, will return at least 31 samples to Earth in 2031. Jezero crater contains various lithologies, including igneous and sedimentary rocks, with ages varying between ~4.0 and 2.6 Ga [26, 27]. The iMOST report includes 7 objectives and wishlist for the returned samples [28]. Returned samples will allow to conduct state-of-the-art Earth-based laboratory analyses on samples with field context (which meteorites do not have) to better constrain martian geology from the Noachian until the Amazonian.

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