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Fundamental constraints and questions from the study of martian meteorites and the need for returned samples

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Physical materials from planetary bodies are crucial for understanding fundamental processes that constrain the evolution of the solar system, as samples can be analyzed at high precision and accuracy in Earth-based laboratories. Mars is the only planet outside of Earth from which we possess samples in the form of meteorites. Martian meteorites (n > 350) have enabled constraints to be placed on various aspects of the red planet's formation and evolution, notably: that Mars accreted and differentiated rapidly; that the planet has a complex volatile element evolution; and that it has always been volcanically active with a rich and diverse magmatic history. Meteorites have limitations, however, with lack of field context, restricted lithological diversity compared to the martian surface, and with no sampling of a major portion of Mars' history between 4.1 and 2.4 billion years ago. Returned samples from Mars have the potential to fill these gaps and answer many open questions driven by the study of meteorites, as well as reveal new fundamental research questions. Key questions that Mars Sample Return is likely to answer regard the basic evolution of the martian interior and surface, its potential for habitability and the possibility of past life, and calibration of age dating of the martian surface. Samples of various lithologies and different ages collected at Jezero crater by the *Perseverance* rover will aid in better understanding our own planet and will answer outstanding questions regarding Mars' future geological evolution and habitability.

Mars | meteorites | planetary processes | returned samples

Why Study Martian Samples?

Much of what we understand about the compositions, ages, and formation of planetary bodies comes from the study of physical samples. For Earth, and even the Moon, such samples are available as materials collected at the surface in dedicated field campaigns. These well-characterized samples have been central to understanding of key processes, including plate tectonics on Earth (e.g., ref. 1), and the importance of complete melting to form a volatile-depleted Moon (2), likely as a consequence of an Earth-Moon forming giant impact event. More recently, planetary samples have enabled assessment of key processes operating during the formation and consequent evolution of the solar system. Although some of these samples have been returned by spacecraft [e.g., Asteroid Bennu sampled by the NASA OSIRIS-Rex mission (3) and asteroids Itokawa and Ryugu sampled by the JAXA Hayabusa and Hayabusa2 missions] or by humans (the Apollo lunar sample suite), the majority of planetary samples have arrived to Earth in the form of >74,000 meteorites (Meteoritical Bulletin, https://www.lpi.usra.edu/meteor/). Meteorites are ejected from their parent body during an impact and subsequently fall on Earth or other planetary bodies. Most meteorites originate from asteroids; some are from Earth's moon, with the only planet from which we knowingly possess meteorites being Mars.

Originally, what we now know of as martian meteorites were thought to originate from the asteroid belt. This was until McSween and Stolper (4) outlined arguments for their martian origin based on their crystallization ages, mineralogy, and chemical compositions. The martian origin theory was effectively proven by Bogard and Johnson (5), who analyzed gas compositions (nitrogen, carbon, and noble gasses) trapped in minerals and impact melt glass in shergottites, the most common class of martian meteorite (6). They found that the trapped gas within the shergottites matched the composition of the martian atmosphere, measured on the surface in 1976 by the Viking landers (7). We have now refined classification techniques to identify martian meteorites: Their distinctive oxygen isotopic compositions and iron to manganese ratios are used to effectively delineate martian meteorites from meteorites from other parent bodies (8).

Meteorites are the only samples that we currently possess from Mars. The evolution of Mars, including models for its bulk composition, the history of its formation and differentiation, the chemistry and mineralogy of igneous (otherwise referred to as magmatic) environments, impact and alteration processes, and the timing of all of those processes, have all been informed by the study of martian meteorites. Furthermore, it is now known that martian meteorites originate from different locations at the surface (>11 locations; ref. 6), enabling the study of Mars at a "planetary scale."

Mars' surface has been explored by landers and rovers since the touchdown of the Viking landers in 1976. To date,

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however, mass and technological constraints for such spacecraft prevent them from conducting analyses with the precision and accuracy available in terrestrial laboratories. This includes accurately and precisely probing the ages, compositions, and physical properties, including magnetic and microscopic characteristics of rocks on Mars' surface. By contrast, martian meteorites have been analyzed with a battery of highly precise and accurate techniques in Earth-based laboratories, enabling the analysis of elemental abundances down to picogram per gram (pg/g, or $1/10^{-9}$ parts by weight) levels, and isotopic ratio measurements of certain radionuclides with precisions of better than 10 parts per million at two sigma error (e.g., refs. 9, 10). This ability to make precise and accurate measurements has enabled constraints on the timing and nature of key processes in Mars' history, including its accretion, differentiation, and later evolution.

Constraining martian geological and environmental evolution, although the entirety of the red planet's history requires the study of returned samples that would also allow for a better comparison of Mars with Earth and the inner terrestrial planets, from the deep interior to the atmosphere. For example, by studying the atmospheric Roubion sample already collected by the *Perseverance* rover, it should be possible to constrain the modern martian atmospheric composition to high resolution and thus better understand the formation of atmospheres on small rocky planets (10). Additionally, the Earth's geological record is limited to only minerals from the Hadean and strongly metamorphosed and weathered rocks from the Archean. By contrast, martian meteorites are already known to span a range of crystallization (= formation) ages from ~4.4 to 0.15 billion years old (= Ga) and, given an absence of plate tectonics on Mars, returned samples may be somewhat representative of the early Earth, which also likely did not immediately experience plate tectonics (11). The study of Mars therefore has the potential to unravel the early geology of our own planet. Exploring possible life and habitability on Mars could also reveal clues for the timing and the environments required for the onset of life on Earth.

Mars returned samples will benefit future generations of researchers in a manner similar to the Apollo samples, which are still intensively studied by scientists today, 55 y after the Apollo 11 mission. Lunar meteorite and Apollo studies complement one another, each sample type filling knowledge gaps imposed by the other: Both are necessary and are interdependent. Similar to the lunar meteorite and Apollo samples, martian returned samples will help contextualize all future meteorites. The Mars Sample Return mission, prior to human exploration of the red planet, will provide the most pristine sample set of this as-of-yet relatively untouched world. Mars exploration provides us with the earliest chapters of planet formation in the solar system—chapters which are missing or incomplete on more dynamic planets, such as Earth and Venus. Mars is also more accessible than Venus, which has an almost inescapably thick atmosphere. The journey to Mercury is much longer, and its proximity to the Sun means it is not a priority in the search for habitable environments in our solar system. In this sense, one of our closest neighbors, Mars, is a benign planet, where the geological record has been preserved for billions of years. In this paper, we outline some of the fundamental observations made from the study of martian meteorites and some of the key questions that remain regarding the origin and evolution of Mars that cannot be answered solely through the study of martian meteorites.

A Diverse Collection of Martian Meteorites

Currently, more than 370 meteorites have been officially classified as martian, altogether weighing 329 kg (725 lbs,

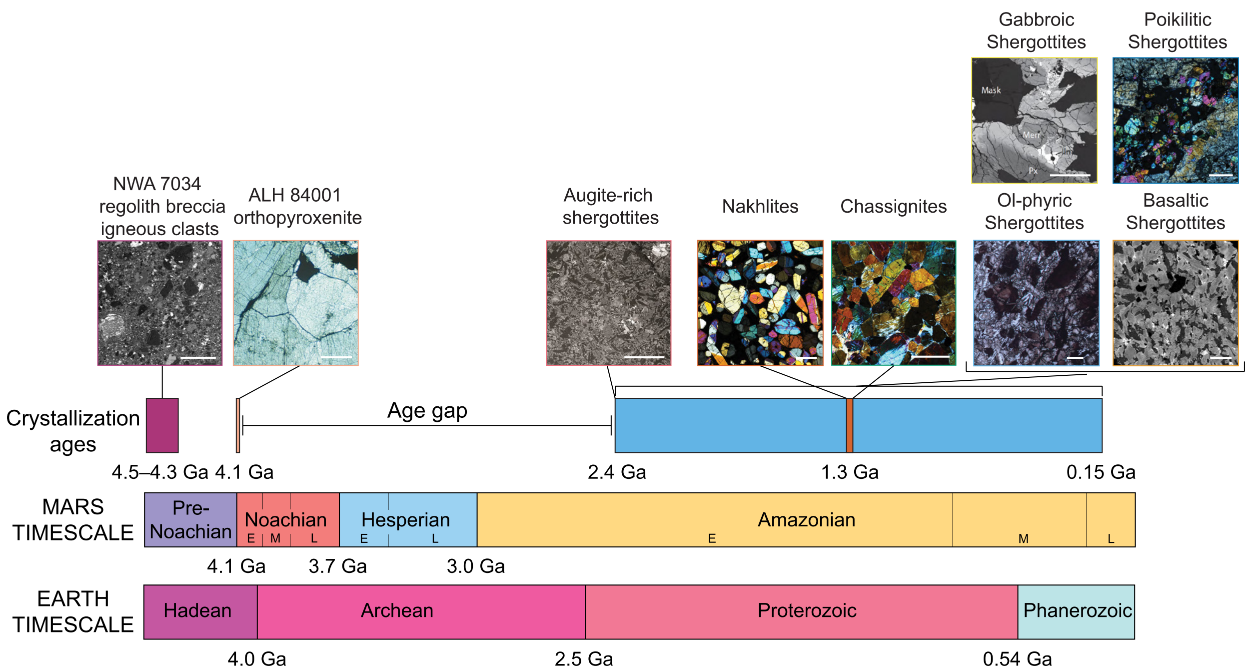

Fig. 1. Timeline of crystallization of martian meteorites, with a large age gap between 4.1 Ga and 2.4 Ga. Martian timeline with age periods from (14), with chronology with thinner lines representing different divisions of martian periods (e.g., E: early, M: mid, and L: late). Crystallization ages from references within (6). Thin section images (from older to younger): Regolith breccia NWA 7034 (BSE image); Orthopyroxenite ALH 84001 (XPL image, courtesy of Allan Treiman, Lunar and Planetary Institute); Augite-rich shergottite: NWA 8159 (BSE image from 12); Nakhlite: MIL 090030 (XPL image) and Chassignite: NWA 2737 (XPL image); Olivine-phyric shergottite: LAR 06319 (XPL image). Scale bars represent 500 microns for thin section images.

Meteoritical Bulletin). These meteorites represent 246 pairing groups; paired meteorites originate from a single meteor that broke up during Earth atmospheric entry. The first martian meteorite was discovered after its observed fall in Chassigny (central France) in 1815. Since 2013, the number of recovered meteorites has increased considerably, with most of these rocks being recovered from the Saharan desert (*SI Appendix*, Fig. S1). Isotopic analyses reveal that meteorites were all ejected from the surface of Mars during impact events between 20 million years ago and 700,000 years ago (e.g., refs. 12, 13).

Martian meteorites are divided into three groups, which are together traditionally termed "SNC": shergottites, nakhlites, and chassignites. There are additionally two individual rocks: Allan Hills (ALH) 84001 and Northwest Africa (NWA) 7034 and its 17 paired meteorites (Figs. 1 and 2). These rocks all have mafic and ultramafic compositions, meaning that their bulk magnesium oxide (MgO) falls between 4 and 30 wt.%, and bulk silica (SiO_2) is between 34 and ~52 wt.% (6). They are all rocks derived either directly or indirectly (NWA 7034, see below) from magmatic processes [(6) and references therein]. Compositions, mineralogies, crystallization and ejection ages, and isotopic compositions of the different martian meteorites are summarized in Table S1.

The shergottites are the most common martian meteorites, making up 88% of the collection in number (including pairings). The magmas which formed shergottites were generated from distinct reservoirs within the mantle of Mars (6). Shergottite samples vary in texture (size, shape, and abundance of minerals), which is controlled by different magma emplacement processes. Most shergottites are younger than ~700 million years, except for two (NWA 7635 and NWA 8159) meteorites, which are both ~ 2.4 Ga (6, 20, 21) and references therein). The nakhlites are clinopyroxene-rich rocks, and chassignites are olivine-rich. There are a total of 35 known nakhlites and chassignites, which have many compositional similarities, share a common formation age (1.3 Ga), and originate from the same volcanic system (22–24). These are therefore the most complete suite of rocks from a single planetary magmatic system outside of Earth. The ALH 84001 meteorite, found in Antarctica, is 4.1 Ga (25) and mostly consists of low-calcium pyroxene. This rock is also one of the most famous meteorites, as it was argued to contain evidence of life from Mars in the form of organic molecules and magnetite minerals shaped as though they were formed by magnetobacteria (25, 26). Several studies have since shown that similar magnetite can form through shock metamorphism (27). The controversy surrounding ALH 84001 nonetheless accelerated martian exploration.

All the above meteorites were emplaced at the martian surface as lava flows, or close to the surface as shallow intrusive rocks (e.g., dykes, sills), or in the subsurface as plutonic cumulates. The NWA 7034 meteorite, however, is unique: It is a polymict regolith breccia, consisting of angular fragments (or clasts) of other rocks from different origins which are amalgamated together, likely through an impact or multiple impacts (28). Northwest Africa 7034 is composed of igneous or impact clasts (29) that are up to 4.5 Ga, which are older than the Jack Hills zircons, the oldest terrestrial minerals [~4.4 Ga; (24)].

What Critical Knowledge Have We Gained from Martian Meteorites?

As noted in the following section, martian meteorites have helped us understand various aspects of the red planet:

Mars Has Always Been a Volcanically Active Planet. While remote sensing imagery can yield the relative age of an extraterrestrial surface via crater counting (30), Earth-based laboratory equipment can provide precise quantitative ages. Meteorites can record crystallization, ejection, alteration,

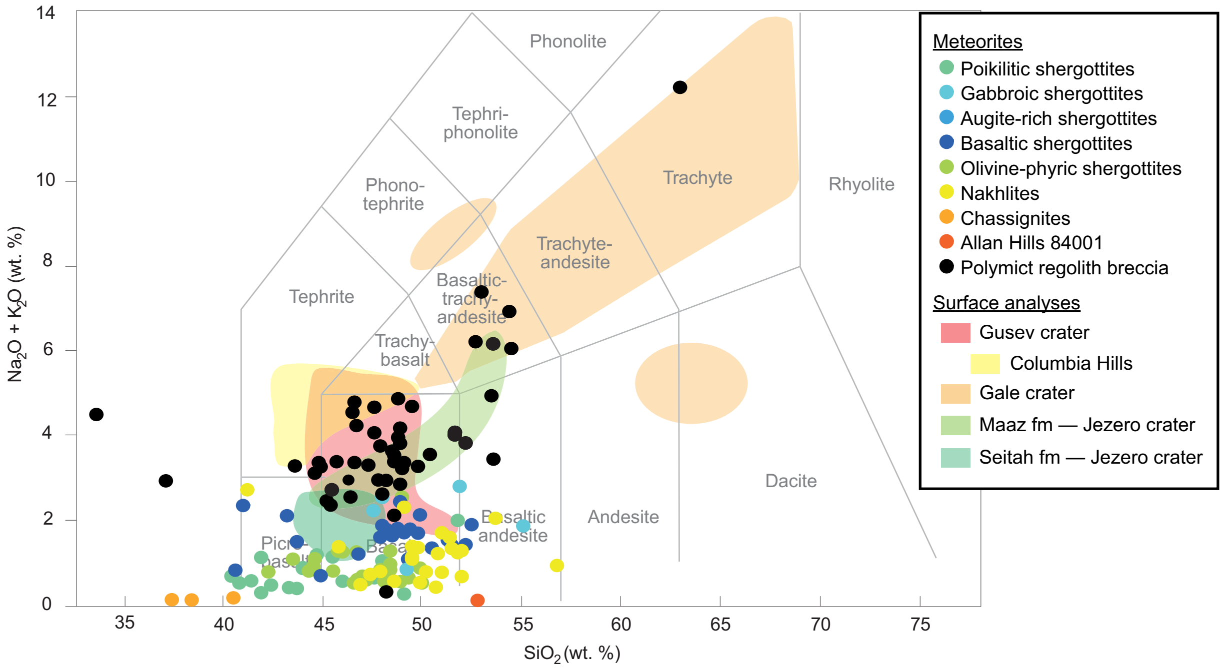

Fig. 2. Total alkali–silica element diagrams of most martian igneous rocks analyzed through meteorite studies (see ref. 7 and references therein), rocks from Gusev crater (15, 16), and rocks from Gale crater (17) as well as Máaz and Séítah formation from Jezero crater (18, 19). Most current martian samples are mafic to ultramafic in composition.

and impact ages. Martian magmatic meteorites crystallize with either old (Noachian, 4.5 to 4.1 Ga; ALH 84001/NWA 7034) or relatively young ages (Amazonian, 2.4 Ga to 150 Ma; see Fig. 1), but there are no existing ages from meteorites in between (Fig. 1). Approximately 75% of the surface of Mars is Noachian to Hesperian in age (31), whereas the vast majority of meteorites were formed during the Amazonian, suggesting that meteorites do not provide a comprehensive understanding of the martian rock record. Evidence from meteorites for magmatism at the beginning of martian geologic history to more recent times implies that convection of its interior occurred since 4.5 Ga and is likely still happening (32).

Mars' Mantle Differentiated Early in Its Geologic History. All igneous rocks, martian included, can retain the minor to trace (<0.1% by weight) element and isotopic characters of their source, which are reflective of the mantle (or occasionally crustal) rock that partially melted to generate a parent magma. Earth-based laboratory analyses are necessary to study trace element abundances and isotopes at sufficient precision and accuracy for appropriate interpretation, and such studies of martian meteorites have revealed that at least five different sources exist or have existed on Mars (Fig. 3). Shergottites likely originate from three of those sources, which are referred to as enriched, intermediate, or depleted according to the relative abundances of particular trace elements (called rare earth elements, or REE), and by ratios of their radiogenic isotopic compositions (e.g., decay of ^{87}Rb and ^{147}Sm to produce long-term, time-integrated ^{87}Sr/^{86}Sr versus ^{143}Nd/^{144}Nd variations, respectively; see Borg et al., this volume). Allan Hills 84001 originates from a reservoir similar to the enriched shergottites (Fig. 3). The nakhlites and chassignites originate from a single distinct source (6, 23), and igneous clasts of NWA 7034 represent at least one source (e.g., ref. 29). Critically, all of these reservoirs formed early in martian geologic history around ~4.4 Ga, shortly after the separation of its core, mantle, and crust, and show no evidence of remixing since that time (e.g., refs. 32, 33). These studies indicate that the martian interior is heterogeneous in terms of trace elements and isotopes. This observation is somewhat surprising, as convection must have played an important role in the martian evolution for 4.5 billion years and the generation of recent volcanism on the planet.

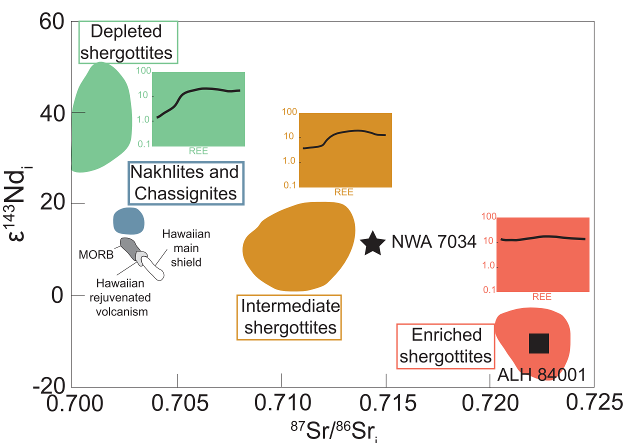

Fig. 3. Initial ε^{143}Nd$_i$ and ^{87}Sr/^{86}Sr$_i$ bulk compositions of martian meteorites, including the three different types of shergottites (depleted, intermediate, and enriched), nakhlites and chassignites, ALH 84001, and NWA 7034 modified from (6), with terrestrial compositions from (34). The current martian meteorites show diverse isotopic compositions.

Isotope Data Suggest Very Early and Rapid Planet Accretion and Formation of the Martian Core and Mantle. Isotope analyses (including the now-extinct ^{182}Hf-^{182}W and ^{146}Sm-^{142}Nd systems) allow precise constraints on accretion of Mars and the formation of its core and mantle. The accretion of Mars and its core formation are now estimated to have taken place around 5 to 10 million years after the oldest components in the solar system [which are called Calcium Aluminum inclusions (CAIs)] (35, 36). Dauphas and Pormand (35) showed that Mars accreted very rapidly, in a period of ≤1.8 million years, which took place at the same time as the formation of small ~10 to 100 km diameter planetary bodies in the solar system. Because of such an early accretion age, Mars was potentially able to incorporate enough ^{26}Al, a heat-producing and short-lived isotope, in order to completely melt and create a magma ocean (=planetary-scale melting). Conversely, Earth likely accreted over 10 s of millions of years, with completion around 50 to 100 million years after CAI (35, 37).

Post-Core Formation Late Accretion Similar to Earth. Martian meteorites have been analyzed for the abundances of ultratrace elements (<0.001% by weight), such as the highly siderophile elements (HSE). The HSE, which include osmium, iridium, ruthenium, platinum, palladium, and rhenium, are strongly partitioned into the metal core during core-mantle differentiation processes. Consequently, Mars' silicate mantle and crustal reservoirs should be depleted in the HSE, with very large interelement (e.g., Re/Os) fractionations. In contrast, it has been shown that martian meteorites come from partial melting of reservoirs in Mars with similar relative and absolute enrichments of the HSE to Earth (9, 38). The mantle of Mars has chondritic relative abundances of the HSE suggesting ~0.6 to 0.7% mass addition after core formation (38). The HSE appear to be quite well mixed within the martian mantle, which further indicates that post-core formation late accretion occurred before the isolation of mantle reservoirs ("*Mars' mantle differentiated early in its geologic history*"). The similarity in post-core formation additions to Mars and Earth is important for dynamical models of accretion (e.g., ref. 39, 40). Mars is closer to potential noncarbonaceous (inner solar system) and carbonaceous (outboard of Jupiter) sources of late-accretion materials, making further study of martian materials important for understanding wider solar system evolution (41)

Evidence of Surficial Weathering Processes, Atmosphere–Solid Mars Interactions, and Water. Martian meteorites contain abundant evidence for the formation of secondary materials that were formed after their crystallization on the surface of Mars. Such secondary materials are common in terrestrial rocks through weathering processes, indicating a similar mode of origin for martian secondary minerals through interactions with near-surficial or surficial water. Iddingsite (i.e., alteration products from olivine) and minerals resulting from martian low-temperature alteration processes, such as siderite (Fe-carbonates), phyllosilicates, evaporites, and possibly salts, are found nearly ubiquitously in all nakhlites (42–44). The meteorite ALH 84001 includes carbonates, whereas shergottites contain carbonates and clays (45), and the polymict regolith breccia has experienced hydrothermal alteration (46, 47). In addition to this physical evidence for alteration, studies of sulfur isotopes in martian meteorites have revealed a close link between alteration and atmospherically produced mass independently fractionated sulfur isotopes (48), with coupled S-Os isotopes, indicating assimilation of altered ancient martian crust (24). Martian meteorites therefore reveal an active atmospheric-ground water cycle on Mars at certain stages in its past. Less clear is whether this cycle was ephemeral, driven by localized magmatism, or was long-lived.

Was Mars Volatile-Enriched or Volatile-Depleted? Evidence from remote sensing and rover data suggests that the water cycle on Mars was active and extensive during the planet's early history, possibly akin to that of Earth (e.g., ref. 49). Martian meteorite hydrogen isotope (D/H) data from both primary and secondary minerals, however, suggest that this water was largely lost via atmospheric stripping (50). Such observations are consistent with mass fractionation of Xe isotopes in martian meteorite gas, interpreted to reflect the martian atmospheric composition, suggesting preferential ionization and loss of the lighter isotopes of Xe during escape of H from the martian atmosphere (e.g., ref. 51). The remaining, much thinner, atmosphere of Mars is CO_2-enriched, and there is evidence from the nakhlite meteorites that this CO_2 has resulted in carbon sequestration within the martian igneous crust via a process of mineral carbonation (olivine conversion to the Fe-carbonate siderite) (52). In addition to carbonates, macromolecular carbon is ubiquitous within meteorites and appears to originate from the mantle (e.g., ref. 53). Furthermore, the Rb/Sr and K/U ratios of martian meteorites potentially indicate a volatile-rich interior for Mars (e.g., ref. 54), yet studies of the stable isotope compositions of the moderately volatile elements Zn and K suggest that Mars experienced significant volatile depletion (55, 56). These results are consistent with a likely size threshold at which planets are unable to retain significant volatiles, with Mars apparently lying at the lowermost bounds of such a threshold (55).

Meteorites Enable Investigation of Emplacement and Magma Differentiation Processes. Direct and indirect studies on martian meteorites have enabled quantitative and qualitative constraints to be placed on the formation conditions (pressure and temperature) of their minerals, the durations for which their parent magmas were stored in the subsurface, and how the magmas were finally emplaced on or near the surface. These approaches have included the direct study of meteorites (e.g., ref. 6), empirically derived constraints from experimental petrology (57), and theoretical calculations (22, 58). Both intrusive igneous rocks and extrusive lavas are evident in the martian meteorite collection (6) and were emplaced as lava flows, subsurface sills, and possibly plutons, similar to emplacement mechanisms observed for terrestrial magmas. Some meteorites, such as nakhlites and chassignites, can be grouped together as a coherent suite of rocks, implying that they all originate from the same location and volcanic system on Mars, on the basis of shared ejection ages. Textural studies enable determination that most martian meteorites were emplaced in ways similar to terrestrial rocks, for example, as a series of related lava flows (22). The different textural subclasses of enriched or depleted shergottite groups could also come from the same magmatic system. These shergottite groups, which derive from different mantle sources, are separately linked through a magmatic differentiation process called fractional crystallization—a common process on Earth (59, 60). However, magmatic differentiation processes that lead to more evolved compositions (richer in silica), are not clearly recorded in the meteorite collection (58).

Magma Compositions Have Evolved Over Time. Although we only have two basaltic meteorites dating from the Noachian, compositions and mineralogical differences can be observed between these rocks and younger basaltic rocks. For example, orthopyroxene, a Mg-rich and Ca-poor pyroxene endmember, is more prevalent in older rocks (as also observed by orbit) (6, 61). Water content seems to also have decreased with time in martian magmas (50, 62). In addition, more evolved compositions have been observed in NWA 7034, and not in the Amazonian meteorites. These lines of evidence, from both meteorites and surface observations, possibly indicate that evolved rocks could have been more common early in Mars's history. They also provide the possibility that water loss from Mars throughout its history has fundamentally shaped its magmatic evolution.

Insight into Mars' Magnetic Field. Weak magnetic fields above many large martian impact basins have been observed from orbit and are commonly interpreted to show that Mars's dynamo shut down before 4.0 Ga (e.g., ref. 63). Conversely, Allan Hills 84001 records evidence for strong magnetic fields for Mars around 4.1 to as late as 3.7 Ga, which could be explained by a late cessation of the martian dynamo. Furthermore, the 1.3 Ga nakhlites show a possible crustal local magnetization (64), providing evidence for a protracted history of magnetism within Mars.

Current Limitations Imposed by the Available Martian Meteorite Inventory

Despite the many contributions enabled by the study of martian meteorites, key areas are identified where Mars Sample Return is required to address unanswered problems:

1. *Absence of field context.* Although we know when individual martian meteorites were ejected, we do not know the exact location on the surface that they were ejected from. There have been several proposals for source craters of different groupings of meteorites, most of which are located in the Tharsis province (for some of the shergottites) and the Southern Highlands (for NWA 7034) (20, 65, 66), and a recent study was able to better constrain source crater locations (67). Even if a source crater were to be unambiguously identified for a meteorite, its field context cannot be determined with accuracy, which would otherwise serve as a crucial requirement to constrain its emplacement history and environment to establish the geological history of that area. Selecting martian samples at an outcrop for return is the only means with which to address this shortcoming—a task currently being undertaken by the *Perseverance* rover on Mars.

2. *Gap in age record.* No martian meteorites were formed between 4.1 and 2.4 Ga, and then between 2.4 Ga and ~1.3 Ga, which comprises a large fraction of the planet's age (Fig. 2). Igneous processes occurring from the mid-Amazonian to the present day are reasonably well represented, as most martian meteorites (n = 242) are younger than/or equal to 1.3 Ga. To bridge the time gap and better understand martian geological evolution from 4.5 Ga to the present, the sample collection needs to be enhanced by sampling for unrepresented ages.
3. *Biased samples of the crust.* Martian meteorites do not seem to represent the bulk of the martian crust. Martian meteorites overall display different compositions than those observed at the martian surface by rovers: Martian meteorites have lower silica, lower alkali elements, and higher MgO and CaO contents relative to martian surface rocks (Fig. 2). This discrepancy has not been explained, but is likely due to differences in ages and mantle sources. Martian meteorites are much younger than most of the martian surface, as more than 50% of the surface is older than 3.7 Ga (68).
4. *Lack of lithological diversity.* While there has been an increase in the quantity of martian meteorite finds over the last decade that have expanded the compositional, textural, and mineralogical range of the sample collection, all (except a few clasts in NWA 7034) are mafic and ultramafic in composition. However, rovers have found significant diversity at the few locations they have explored, including alkaline and evolved compositions, representing magmatic processes distinct from those recorded in martian meteorites (15, 17). Sedimentary rocks in various environments have also been analyzed at the surface by rovers and orbiters.
5. *Mechanical sampling biases.* Due to the process of impact on the martian surface required to spall meteorites, it is likely that well-consolidated igneous rocks from Mars are preferentially sampled during the ejection process. The martian meteorites are dominated by igneous rocks that have avoided extensive aqueous alteration and which crystallized recently on or near the martian surface. This bias is due to the fact that only more competent rocks, representing younger rocks with low degrees of alteration, are able to survive the impact ejection process (69, 70). In addition, older terrains on Mars are covered with a thicker regolith layer than are younger terrains, which limits chances of ejection of underlying material (71). This goes some way to explaining why >95% of the martian meteorites are Amazonian (<3.7 Ga), whereas >75% of the surface of Mars is Noachian or Hesperian (>3.7 Ga) (68). Mars Sample Return will rectify this bias sampling by bringing back samples that increase the diversity of available rocks.

What Are the Critical Questions that Remain Unanswered?

With every new finding resolved by martian meteorites, new questions are brought to light. Rover analyses can aid in answering these questions. However, rover instruments cannot analyze with the precision and high resolution required to answer the remaining questions about Mars. To be able to conduct state-of-the-art geochemical, petrological, and geochronological analyses on geological materials with field context, returned samples are needed.

Heterogeneity and Evolution of the Martian Interior and Surface. With the expansion of the martian meteorite collection by ~73% since 2011 (Fig. 1), various magma sources have been found. These reservoirs have retained long-term radiogenic isotopic compositions consistent with relative isolation since their formation (72–74). Thus, many open questions arise from our findings in studying martian meteorites:

- How and when did the martian interior evolve in terms of composition and mineralogy? Martian meteorites are not representative of the many compositions of rocks observed by lower-resolution instruments onboard rovers and orbiters.
- What types of igneous rocks were formed between 4.1 and 2.4 billion years? What magmatic processes occurred during this time; for example, is there a greater diversity of more evolved rock types than recorded in meteorites younger than 2.4 Ga?
- What is the extent of compositional diversity on the martian surface? How common are evolved rocks on Mars and when and how were they formed?
- What was the origin and composition of the primary martian crust and what were its properties (thickness, density)? What role did a magma ocean play in its formation?
- What is the field context of igneous rocks on Mars (e.g., intrusive versus extrusive)?
- How many different reservoirs are present in the martian interior? Why have martian magma source reservoirs not seemingly evolved with time, even if there is evidence for vigorous convection on Mars, which would have the effect of (at least partially) homogenizing the interior?
- When exactly did the Mars magnetic field weaken? How does this relate to continued magmatic processes on Mars evident from meteorites, and what effect did the magnetic field have on the retention or loss of its atmosphere? Why do we observe local magnetization throughout martian geologic history?
- Finally, what do all of these processes reveal about planetary habitability?

Volatiles, life, and habitability. Martian meteorites show the effects of aqueous alteration, or alteration in the presence of liquid water, which occurred prior to their ejection from Mars. However, on Earth, the best-preserved biosignatures and volatile records are not in altered igneous rock, but in the sedimentary and hydrothermal rocks, which are largely missing from the meteorite record (75). Zircons—resilient minerals frequently leveraged for geochronology—from NWA 7034 are unaffected by the life-limiting shock pressures seen in ancient terrestrial and lunar samples (76), meaning that the surface of Mars could have been quiescent and possibly habitable from 4.2 Ga to 3.5 Ga, as water largely dissipated (77). Lithologically diverse samples, including sedimentary rocks, from a known location on Mars would help resolve some of the many questions that arise:

- How did the martian volatile (water and atmospheric gas) cycles evolve during the 4.1 to 2.4 Ga period?
- What were the past climate conditions of Mars, and when was it possibly habitable? Without sedimentary samples, the conditions ranging from fluvial (river) to deltaic or even glacial environments cannot be studied.

- The spatial and temporal extent of the magnetic field of Mars has implications on habitability: Would obtaining potentially magnetized material from a previously unsampled age extend the age boundaries of habitability?
- Can we find evidence of past life on Mars in carefully collected samples?

Martian Crater Counting Calibration. Researchers can estimate the age of the martian surface by measuring the spatial density of overlapping craters: Simplistically, the more heavily cratered a surface, the older it is. This method was developed first for the lunar surface, where cratering events were sampled by Apollo astronauts and were precisely age-dated. There are currently no direct age dates of known martian craters, except one K-Ar age of sandstone at Gale crater (78). In fact, the crater counting chronology for Mars is currently calibrated to the lunar crater counting chronology (79). This calibration can lead to relative age dating errors from crater counting since Mars likely underwent a distinct impact history to the Moon. Therefore, an outstanding question remains: What are the accurate ages for martian surface terrains? A returned sample from a laterally continuous surface with a known crater retention age, or from an impactite that could date a significant impact event, would allow us to revise crater counting techniques for Mars (e.g., ref. 65). The terrain could be more accurately dated to better contextualize the global martian surface ages.

How do Samples Collected by Jezero Answer Those Questions? Shortcomings in the martian meteorite collection are largely based in sampling without known provenance and in biases for age (too young) and for composition (e.g., no sedimentary rocks). The samples collected by the *Perseverance* rover, which landed at Jezero crater in February 2021, at least partially address each of these issues. Rocks are well documented for spatial context upon collection, so they have field context. Although high-fidelity geochronology cannot be conducted by a rover, crater counting estimates place Jezero crater at the boundary of the Noachian and Hesperian (Fig. 4; ref. 80), which has not yet been sampled by meteorites. In addition to igneous rocks, *Perseverance* collected various sedimentary rocks (12 cores in early 2024), including sandstones and mudstones, possibly representing multiple depositional environments, and serving as a climate record (e.g., ref. 81). In addition, by using igneous detrital minerals within these sedimentary rocks, we can constrain igneous processes and sources of these rocks as done in Gale crater (82). The Jezero samples will enable possibly Noachian to Amazonian geochronology (83, 84). Over the past three years, *Perseverance* drove through three main units, including the crater floor. These represent igneous units (18, 19, 85); including the Máaz formation, which are basaltic lavas and pyroclasts, and the Séítah formation, which consists of olivine cumulates; Fig. 2), the western fan, and the margin unit (86), on the way to the crater rim. As shown in Fig. 4, we anticipate Hesperian to Noachian ages for the crater floor. This unit could help revise the martian cratering calibration, although some challenges due to secondary processes (erosion and aeolian processes) may arise (83, 84, 87, 88). We expect the western fan rocks to be around 3.2 to 3.6 Ga (89), whereas the margin unit rich in carbonates and olivine is expected to be Noachian in age (81, 84).

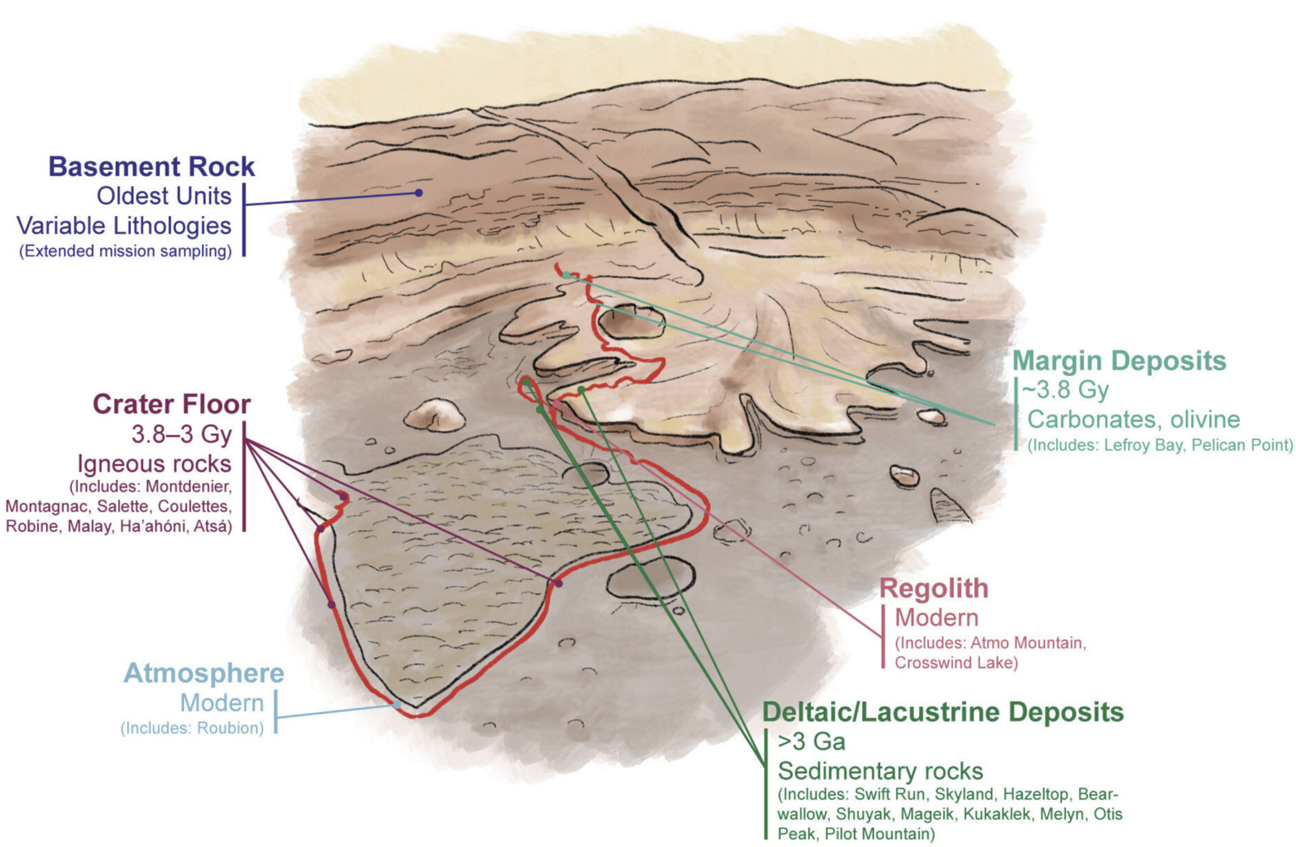

Fig. 4. Illustration overview of Jezero crater showing the different units (and atmospheric and regolith samples) already sampled by the *Perseverance* rover, including their cratering ages and the names of the cached samples (81, 84, 88, 89).

The breadth of samples already collected in Jezero crater in terms of lithologies, compositions, and ages will help better answer the above questions (10).

The sampling by the *Perseverance* rover and successful return of these samples to Earth will provide a single well-studied calibration for Mars. It will not reveal Mars' entire geological diversity or range of environments. With martian meteorites, however, these returned samples will provide unprecedented knowledge to be gathered on the formation of Mars, the formation of planets in general, and clues to the origins of life in the Universe.

Data, Materials, and Software Availability. All study data are included in the article and/or *SI Appendix*.

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1. K. C. Condie, C. K. Shearer, Tracking the evolution of mantle sources with incompatible element ratios in stagnant-lid and plate-tectonic planets. *Geochim. Cosmochim. Acta* **213**, 47–62 (2017).
2. J. M. D. Day, F. Moynier, C. K. Shearer, Late-stage magmatic outgassing from a volatile-depleted Moon. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 9547–9551 (2017).
3. D. S. Lauretta *et al.*, Spacecraft sample collection and subsurface excavation of asteroid (101955) Bennu. *Science* **377**, 285–291 (2022).
4. H. Y. McSween, E. M. Stolper, Basaltic meteorites. *Sci. Am.* **242**, 54–63 (1980).
5. D. D. Bogard, P. Johnson, Martian gases in an antarctic meteorite? *Science* **221**, 651–654 (1983).
6. A. Udry *et al.*, What martian meteorites reveal about the interior and surface of mars. *J. Geophys. Res. Planets* **125**, e2020JE006523 (2020).
7. A. O. Nier *et al.*, Composition and structure of the martian atmosphere: Preliminary results from viking 1. *Science* **193**, 786–788 (1976).
8. A. Ali, I. Jabeen, D. Gregory, R. Verish, N. R. Banerjee, New triple oxygen isotope data of bulk and separated fractions from SNC meteorites: Evidence for mantle homogeneity of Mars. *Meteorit. Planet. Sci.* **51**, 981–995 (2016).
9. A. D. Brandon *et al.*, Evolution of the martian mantle inferred from the ^{187}Re–^{187}Os isotope and highly siderophile element abundance systematics of shergottite meteorites. *Geochim. Cosmochim. Acta* **76**, 206–235 (2012).
10. C. D. K. Herd *et al.*, Sampling Mars: Geologic Context and Preliminary Characterization of Samples Collected by the NASA Mars 2020 Perseverance Rover Mission. *PNAS*, (2024).
11. R. M. Palin, M. Santosh, Plate tectonics: What, where, why, and when? *Gondwana Res.* **100**, 3–24 (2021).
12. H. Y. McSween, Petrology on mars. *Am. Mineral.* **100**, 2380–2395 (2015).
13. R. Wieler *et al.*, Noble gases in 18 Martian meteorites and angrite Northwest Africa 7812—Exposure ages, trapped gases, and a re-evaluation of the evidence for solar cosmic ray-produced neon in shergottites and other achondrites. *Meteorit. Planet. Sci.* **51**, 407–428 (2016).
14. W. K. Hartmann, G. Neukum, "Cratering chronology and the evolution of Mars" in *Chronology and Evolution of Mars*, R. Kallenbach, J. Geiss, W. K. Hartmann, Eds. (Springer, Netherlands, 2001), pp. 165–194.
15. H. Y. McSween *et al.*, Alkaline volcanic rocks from the Columbia Hills, Gusev crater, Mars. *J. Geophys. Res. Planets* **111**, 2006JE002698 (2006).
16. D. W. Ming *et al.*, Geochemical and mineralogical indicators for aqueous processes in the Columbia Hills of Gusev crater, Mars. *J. Geophys. Res. Planets* **111**, 2005JE002560 (2006).
17. A. Cousin *et al.*, Compositions of coarse and fine particles in martian soils at gale: A window into the production of soils. *Icarus* **249**, 22–42 (2015).
18. A. Udry *et al.*, A Mars 2020 perseverance supercam perspective on the igneous nature of the Máaz formation at Jezero Crater and Link with Séítah, Mars. *J. Geophys. Res. Planets* **128**, e2022JE007440 (2023).
19. O. Beyssac *et al.*, Petrological traverse of the olivine cumulate séítah formation at Jezero Crater, Mars: A perspective from supercam onboard perseverance. *J. Geophys. Res. Planets* **128**, e2022JE007638 (2023).
20. C. D. K. Herd *et al.*, The Northwest Africa 8159 martian meteorite: Expanding the martian sample suite to the early Amazonian. *Geochim. Cosmochim. Acta* **218**, 1–26 (2017).
21. T. J. Lapen *et al.*, Two billion years of magmatism recorded from a single Mars meteorite ejection site. *Sci. Adv.* **3**, e1600922 (2017).
22. A. Udry, J. M. D. Day, 1.34 billion-year-old magmatism on Mars evaluated from the co-genetic nakhlite and chassignite meteorites. *Geochim. Cosmochim. Acta* **238**, 292–315 (2018).
23. F. M. McCubbin *et al.*, A petrogenetic model for the comagmatic origin of chassignites and nakhlites: Inferences from chlorine-rich minerals, petrology, and geochemistry. *Meteorit. Planet. Sci.* **48**, 819–853 (2013).
24. J. M. D. Day, M. Paquet, A. Udry, F. Moynier, A heterogeneous mantle and crustal structure formed during the early differentiation of Mars. *Sci. Adv.* **10**, eadn9830 (2024).
25. T. J. Lapen *et al.*, A younger age for ALH84001 and its geochemical link to shergottite sources in mars. *Science* **328**, 347–351 (2010).
26. D. S. McKay *et al.*, Search for past life on mars: Possible relic biogenic activity in martian meteorite ALH84001. *Science* **273**, 924–930 (1996).
27. A. H. Treiman, Uninhabitable and potentially habitable environments on mars: Evidence from meteorite ALH 84001. *Astrobiology* **21**, 940–953 (2021).
28. W. S. Cassata *et al.*, Chronology of martian breccia NWA 7034 and the formation of the martian crustal dichotomy. *Sci. Adv.* **4**, eaap8306 (2018).
29. C. B. Agee *et al.*, Unique meteorite from early amazonian mars: Water-rich basaltic breccia Northwest Africa 7034. *Science* **339**, 780–785 (2013).
30. S. C. Werner, B. A. Ivanov, "Exogenic dynamics, cratering, and surface ages" in *Treatise on Geophysics*, G. Schubert, Ed. (Elsevier, ed. 2, 2015), vol. 10, pp. 327–365.
31. K. L. Tanaka, S. J. Robbins, C. M. Fortezzo, J. A. Skinner, T. M. Hare, The digital global geologic map of Mars: Chronostratigraphic ages, topographic and crater morphologic characteristics, and updated resurfacing history. *Planet. Space Sci.* **95**, 11–24 (2014).
32. W. S. Kiefer, Melting in the martian mantle: Shergottite formation and implications for present-day mantle convection on Mars. *Meteorit. Planet. Sci.* **38**, 1815–1832 (2003).
33. J. W. Valley *et al.*, Hadean age for a post-magma-ocean zircon confirmed by atom-probe tomography. *Nat. Geosci.* **7**, 219–223 (2014).
34. J. M. D. Day *et al.*, Martian magmatism from plume metasomatized mantle. *Nat. Commun.* **9**, 4799 (2018).
35. N. Dauphas, A. Pourmand, Hf–W–Th evidence for rapid growth of Mars and its status as a planetary embryo. *Nature* **473**, 489–492 (2011).
36. T. S. Kruijer *et al.*, The early differentiation of Mars inferred from Hf–W chronometry. *Earth Planet. Sci. Lett.* **474**, 345–354 (2017).
37. A. N. Halliday, R. M. Canup, The accretion of planet Earth. *Nat. Rev. Earth Environ.* **4**, 19–35 (2022).
38. K. T. Tait, J. M. D. Day, Chondritic late accretion to Mars and the nature of shergottite reservoirs. *Earth Planet. Sci. Lett.* **494**, 99–108 (2018).
39. V. Debaille, A. D. Brandon, Q. Z. Yin, B. Jacobsen, Coupled ^{142}Nd–^{143}Nd evidence for a protracted magma ocean in Mars. *Nature* **450**, 525–528 (2007).
40. W. F. Bottke, R. J. Walker, J. M. D. Day, D. Nesvorny, L. Elkins-Tanton, Stochastic late accretion to Earth, the Moon, and Mars. *Science* **330**, 1527–1530 (2010).
41. T. Kleine, T. Steller, C. Burkhardt, F. Nimmo, An inner solar system origin of volatile elements in Mars. *Icarus* **397**, 115519 (2023).
42. L. J. Hallis, H. A. Ishii, J. P. Bradley, G. J. Taylor, Transmission electron microscope analyses of alteration phases in martian meteorite MIL 090032. *Geochim. Cosmochim. Acta* **134**, 275–288 (2014).
43. A. H. Treiman, The nakhlite meteorites: Augite-rich igneous rocks from Mars. *Geochemistry* **65**, 203–270 (2005).
44. A. W. Needham, R. L. Abel, T. Tomkinson, M. M. Grady, Martian subsurface fluid pathways and 3D mineralogy of the Nakhla meteorite. *Geochim. Cosmochim. Acta* **116**, 96–110 (2013).
45. L. Borg, M. J. Drake, A review of meteorite evidence for the timing of magmatism and of surface or near-surface liquid water on Mars. *J. Geophys. Res. Planets* **110**, 2005JE002402 (2005).
46. F. M. McCubbin *et al.*, Geologic history of Martian regolith breccia Northwest Africa 7034: Evidence for hydrothermal activity and lithologic diversity in the Martian crust. *J. Geophys. Res. Planets* **121**, 2120–2149 (2016).
47. Y. Liu, C. Ma, J. R. Beckett, Y. Chen, Y. Guan, Rare-earth-element minerals in martian breccia meteorites NWA 7034 and 7533: Implications for fluid–rock interaction in the martian crust. *Earth Planet. Sci. Lett.* **451**, 251–262 (2016).
48. H. B. Franz *et al.*, Isotopic links between atmospheric chemistry and the deep sulphur cycle on Mars. *Nature* **508**, 364–368 (2014).
49. B. M. Jakosky, L. J. Hallis, Fate of an Earth-Like Water Inventory on Mars. *J. Geophys. Res. Planets* **129**, e2023JE008159 (2024).
50. J. J. Barnes *et al.*, Multiple early-formed water reservoirs in the interior of Mars. *Nat. Geosci.* **13**, 260–264 (2020).
51. K. J. Zahnle, M. Gacesa, D. C. Catling, Strange messenger: A new history of hydrogen on Earth, as told by Xenon. *Geochim. Cosmochim. Acta* **244**, 56–85 (2019).
52. T. Tomkinson, M. R. Lee, D. F. Mark, C. L. Smith, Sequestration of Martian CO2 by mineral carbonation. *Nat. Commun.* **4**, 2662 (2013).
53. A. Steele, F. M. McCubbin, M. D. Fries, The provenance, formation, and implications of reduced carbon phases in Martian meteorites. *Meteorit. Planet. Sci.* **51**, 2203–2225 (2016).
54. A. N. Halliday, Mixing, volatile loss and compositional change during impact-driven accretion of the Earth. *Nature* **427**, 505–509 (2004).
55. Z. Tian *et al.*, Potassium isotope composition of Mars reveals a mechanism of planetary volatile retention. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2101155118 (2021).
56. M. Paquet, P. A. Sossi, F. Moynier, Origin and abundances of volatiles on Mars from the zinc isotopic composition of Martian meteorites. *Earth Planet. Sci. Lett.* **611**, 118126 (2023).
57. J. Filiberto, Geochemistry of Martian basalts with constraints on magma genesis. *Chem. Geol.* **466**, 1–14 (2017).
58. A. Ostwald, A. Udry, V. Payré, E. Gazel, P. Wu, The role of assimilation and fractional crystallization in the evolution of the Mars crust. *Earth Planet. Sci. Lett.* **585**, 117514 (2022).
59. R. R. Rahib *et al.*, Mantle source to near-surface emplacement of enriched and intermediate poikilitic shergottites in Mars. *Geochim. Cosmochim. Acta* **266**, 463–496 (2019).
60. A. H. Treiman, J. Filiberto, Geochemical diversity of shergottite basalts: Mixing and fractionation, and their relation to Mars surface basalts. *Meteorit. Planet. Sci.* **50**, 632–648 (2015).
61. D. Baratoux, M. J. Toplis, M. Monnereau, V. Sautter, The petrological expression of early Mars volcanism. *J. Geophys. Res. Planets* **118**, 59–64 (2013).
62. J. B. Balta, H. Y. McSween, Water and the composition of Martian magmas. *Geology* **41**, 1115–1118 (2013).
63. R. J. Lillis, S. Robbins, M. Manga, J. S. Halekas, H. V. Frey, Time history of the Martian dynamo from crater magnetic field analysis. *J. Geophys. Res. Planets* **118**, 1488–1511 (2013).
64. M. W. R. Volk, R. R. Fu, A. Mittelholz, J. M. D. Day, Paleointensity and rock magnetism of martian nakhlite meteorite miller range 03346: Evidence for intense small-scale crustal magnetization on Mars. *J. Geophys. Res. Planets* **126**, e2021JE006856 (2021).
65. A. Lagain *et al.*, The Tharsis mantle source of depleted shergottites revealed by 90 million impact craters. *Nat. Commun.* **12**, 6352 (2021).
66. A. Lagain *et al.*, Early crustal processes revealed by the ejection site of the oldest martian meteorite. *Nat. Commun.* **13**, 3782 (2022).

67. C. D. Herd *et al.*, The source craters of the martian meteorites: Implications for the igneous evolution of Mars. *Sci. Adv.* **10**, p.eadn2378 (2024).
68. V. Sautter *et al.*, Magmatic complexity on early Mars as seen through a combination of orbital, in-situ and meteorite data. *Lithos* **254–255**, 36–52 (2016).
69. P. H. Warren, Lunar and martian meteorite delivery services. *Icarus* **111**, 338–363 (1994).
70. E. L. Walton, S. P. Kelley, C. D. K. Herd, Isotopic and petrographic evidence for young Martian basalts. *Geochim. Cosmochim. Acta* **72**, 5819–5837 (2008).
71. J. N. Head, H. J. Melosh, B. A. Ivanov, Martian meteorite launch: High-speed ejecta from small craters. *Science* **298**, 1752–1756 (2002).
72. V. Debaille, A. D. Brandon, C. O'Neill, Q.-Z. Yin, B. Jacobsen, Early martian mantle overturn inferred from isotopic composition of nakhlite meteorites. *Nat. Geosci.* **2**, 548–552 (2009).
73. L. E. Borg, G. A. Brennecka, S. J. K. Symes, Accretion timescale and impact history of Mars deduced from the isotopic systematics of martian meteorites. *Geochim. Cosmochim. Acta* **175**, 150–167 (2016).
74. V. Debaille, Q.-Z. Yin, A. D. Brandon, B. Jacobsen, Martian mantle mineralogy investigated by the 176Lu–176Hf and 147Sm–143Nd systematics of shergottites. *Earth Planet. Sci. Lett.* **269**, 186–199 (2008).
75. T. Bosak, K. R. Moore, J. Gong, J. P. Grotzinger, Searching for biosignatures in sedimentary rocks from early Earth and Mars. *Nat. Rev. Earth Environ.* **2**, 490–506 (2021).
76. D. E. Moser *et al.*, Decline of giant impacts on Mars by 4.48 billion years ago and an early opportunity for habitability. *Nat. Geosci.* **12**, 522–527 (2019).
77. J. A. Hurowitz, S. M. McLennan, A ~3.5 Ga record of water-limited, acidic weathering conditions on Mars. *Earth Planet. Sci. Lett.* **260**, 432–443 (2007).
78. P. M. Vasconcelos *et al.*, Discordant K-Ar and young exposure dates for the Windjana sandstone, Kimberley, Gale Crater, Mars. *J. Geophys. Res. Planets* **121**, 2176–2192 (2016).
79. S. J. Robbins, New crater calibrations for the lunar crater-age chronology. *Earth Planet. Sci. Lett.* **403**, 188–198 (2014).
80. S. C. Werner, In situ calibration of the Martian cratering chronology. *Meteorit. Planet. Sci.* **54**, 1182–1193 (2019).
81. T. A. Goudge, J. F. Mustard, J. W. Head, C. I. Fassett, S. M. Wiseman, Assessing the mineralogy of the watershed and fan deposits of the Jezero crater paleolake system, Mars. *J. Geophys. Res. Planets* **120**, 775–808 (2015).
82. V. Payré *et al.*, Constraining ancient magmatic evolution on Mars Using crystal chemistry of detrital igneous minerals in the sedimentary bradbury group, Gale Crater, Mars. *J. Geophys. Res. Planets* **125**, e2020JE006467 (2020).
83. S. Shahrzad *et al.*, Crater Statistics on the dark-toned, mafic floor unit in Jezero Crater, Mars. *Geophys. Res. Lett.* **46**, 2408–2416 (2019).
84. L. Mandon *et al.*, Refining the age, emplacement and alteration scenarios of the olivine-rich unit in the Nili Fossae region. *Mars*. **336**, 113436 (2020).
85. R. C. Wiens *et al.*, Compositionally and density stratified igneous terrain in Jezero crater, Mars. *Sci. Adv.* **8**, eabo3399 (2022).
86. K. M. Stack *et al.*, Sedimentology and stratigraphy of the shenandoah formation, Western Fan, Jezero Crater, Mars. *J. Geophys. Res. Planets* **129**, e2023JE008187 (2024).
87. L. Rubanenko *et al.*, "Chapter 5—Challenges in crater chronology on Mars as reflected in Jezero crater" in *Mars Geological Enigmas*, R. J. Soare, S. J. Conway, J.-P. Williams, D. Z. Oehler, Eds. (Elsevier, 2021), pp. 97–122.
88. C. Quantin-Nataf *et al.*, The complex exhumation history of jezero crater floor unit and its implication for Mars sample return. *J. Geophys. Res. Planets* **128**, e2022JE007628 (2023).
89. N. Mangold *et al.*, Fluvial regimes, morphometry, and age of jezero crater paleolake inlet valleys and their exobiological significance for the 2020 rover mission landing site. *Astrobiology* **20**, 994–1013 (2020).