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Perspectives on Mars Sample Return: A critical resource for planetary science and exploration

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Mars Sample Return (MSR) has been the highest flagship mission priority in the last two Planetary Decadal Surveys of the National Academies of Science, Engineering, and Medicine (hereafter, "the National Academies") and was the highest priority flagship for Mars in the Decadal Survey that preceded them. This inspirational and challenging campaign, like the Apollo program's returned lunar samples, will potentially revolutionize our understanding of Mars and help inform how other planets are explored. MSR's technological advances will keep the NASA and European Space Agency at the forefront of planetary exploration, and data on returned samples will fill knowledge gaps for future human exploration. Investigations of the ancient rocks collected in and around Jezero crater, as well as samples of the regolith and atmosphere, will be fundamentally different in scope, depth, and certainty from what is achievable with spaceborne observations. Returned Mars samples can address critical science issues including the discovery and characterization of ancient extraterrestrial life, prebiotic organic chemistry, the history of habitable planetary environments, planetary geological, geochemical, and geophysical evolution, orbital dynamics of bodies in the early Solar System, and the formation and evolution of atmospheres.

Mars | samples | spacecraft missions

Mars has been a target of scientific interest for centuries, but the vision that we could collect, return, and investigate samples from Mars came to the forefront much more recently—spurred, in part, by debate as to whether the Viking landers detected evidence for life (1, 2). The modern era of robotic exploration of Mars, beginning in the 1990s, has been an unrivaled success story. These spacecraft missions were guided by a philosophy that Mars exploration would be of greatest value if it were conducted as a program of strategically guided missions that orbit, land, and rove across the surface to understand martian geology, water and climate history, and the potential for the development of life beyond Earth. These robotic missions transformed the early view of Mars from one of a cold, dry, lava-covered planet unlikely to have harbored life to the current understanding that liquid water was present at the surface in the past and is likely present in the subsurface today, the climate was very likely once much warmer than it is today, and past conditions probably were habitable (3–5). Although there are still many valuable measurements that can and should be made by orbiting, landed, and roving scientific payloads, we also recognize that there are analyses that either cannot be made with current remote-sensing technology or not with the equivalent fidelity of laboratory facilities on Earth. If we are to address many of the most significant questions about Mars, including the possibility that life may have existed in that early warmer and wetter period and what that means for the origin of life on Earth (and elsewhere), analyzing returned martian samples will accelerate that process by decades for many subjects of interest. In doing so, samples from Mars will produce a significant step forward in scientific understanding of the planet and inform how we can best use robotic programs for future planetary exploration. Sample return is also a long-term investment in science, because a significant portion of the returned material will be held securely for future generations who will develop new questions and measurement capabilities that will leapfrog what we can achieve now.

Numerous reports and scientific papers going back decades describe the myriad scientific subjects that would be advanced by applying state-of-the-art measurement capabilities to samples returned from Mars (6), but we can also look to advances in planetary science resulting from the return of lunar samples by the Apollo missions. Detailed elemental, isotopic, and mineralogical analyses of lunar rocks have resulted in a firmer understanding of the formation of the Earth-Moon system, the abundance of water and other volatiles on the Moon, and the complexity of geologic processes leading to lunar crustal formation (7, 8). Lunar samples have allowed us to place quantitative constraints on the timing, magnitude, and sources of early impact events on the Moon (and the Earth) during a period for which we do not have a terrestrial geologic record. The notion of a "Late Heavy Bombardment" after planet formation is based upon the ages of lunar crater samples and required new models of planetary dynamics (9, 10). A chronology based on quantitative radiometric ages and crater density data for geologic units on the Moon has been extrapolated to other Solar System bodies (11). The return of lunar samples to Earth during the Apollo era complemented and enhanced robotic

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exploration and provided ground truth for remote-sensing measurements, as will be done by sample return from Mars.

To enable the compelling science envisioned for Mars Sample Return (MSR), the scientific community needed to determine where to collect samples that could address specific problems. Early conversations debated the value of so-called "grab bag" sampling versus scientifically selected samples from well-characterized locations. Although most scientists agree that we can learn from any returned samples, two examples reveal the limitations of grab bag sample collection. In the first case, martian meteorites are samples of Mars that reveal much about the recent igneous history of the planet, but because we do not know the locations on Mars from which these rocks were launched into space by impacts, they lack important geologic context (12, 13). In the second example, the *Mars Pathfinder* lander, along with the *Sojourner* rover, investigated loose rocks in a large outflow channel called Ares Valles in 1997. Even as the results of that mission expanded our understanding of the kinds of rocks Mars hosts, some of the data and broader implications are still not completely understood because those rocks are many kilometers distant from their source outcrops and lack geologic context (14, 15). For these reasons, the consensus developed that to truly advance our understanding of Mars through the return of samples, documentation of the geologic context of any returned samples would be crucial. Therefore, samples to be returned from Mars needed to be collected from an accessible region that has been well characterized from orbital observations in terms of age, geology, composition, and habitability, among other characteristics, and that offers a wide range of sample types to address the myriad of critical scientific questions that remain unanswered (16).

In 2003, the first National Academies Planetary Decadal Survey (17) advised that NASA should begin MSR planning so that its implementation could occur early in the 2013 to 2023 decade. In 2011, the next National Academies' Decadal Survey (18) concluded that sufficient robotic reconnaissance had been performed to select an appropriate sampling site that would address most scientific objectives, and that the first flight segment of a series of missions should be the highest priority flagship mission of the coming decade. In response to that recommendation, NASA began the MSR campaign with the Mars 2020 rover, *Perseverance*, which has been characterizing and collecting a set of samples to be returned by future missions (19). Subsequent missions in the MSR campaign include the Sample Retrieval Lander, which will pick up the samples collected by *Perseverance* and launch them into Mars orbit, and the Earth Return Orbiter, supplied by the European Space Agency (ESA), which will capture the orbiting canister containing the samples and return it to Earth. In 2023, the next National Academies' Decadal Survey (20) reaffirmed MSR as the top priority for the U.S. robotic planetary science program, and also validated the broad value of sample return from numerous other destinations throughout the Solar System.

How Will the Nation and Society Benefit from MSR?

MSR is not just about scientific advances, it is also about inspiration, nationally and internationally. NASA has a storied history of remarkable accomplishments, many of which faced steep challenges because they pushed the boundaries of human achievement, including landing humans on the Moon, roving tens of kilometers on Mars, and launching into space the largest, most powerful telescopes ever built. New technologies have been advanced that have ramifications for people's day-to-day lives. NASA accepts these challenges, in the words of John F. Kennedy, "not because they are easy, but because they are hard," and as a result, NASA is a model of technical achievement for the rest of the world. The challenge of the MSR campaign is that it is bigger in scope and ambition than any previous robotic planetary science mission. But the benefits will be tremendous and long-lasting. The idea of sample return inspires current and future generations of scientists and engineers. The scientists who will make some of the most extraordinary discoveries from these samples have not even been born yet but will be motivated by the challenges we accept and overcome today. The task of returning samples from the surface of another planet motivates engineers to solve new problems and implement new capabilities in literal rocket science. More broadly, for decades, space-faring nations and nations that aspire to explore deep space have looked to the United States for leadership and as a model for success. Importantly, MSR fosters collaborations between nations through the NASA-ESA partnership and continues the U.S. legacy of leadership in the peaceful exploration of deep space.

What Technological Advances Will Benefit Solar System Exploration?

The return of samples from another planet to Earth is technologically challenging. MSR will involve an unprecedented number of technological "first-of-its-kind" undertakings that will help keep NASA and ESA on the leading edge of planetary exploration. These include:

- Pinpoint landing. The sample-retrieval spacecraft must land at an accessible location near the *Perseverance* rover carrying the samples.
- Remote transfer of sample tubes from one vehicle to another on the martian surface.
- First launch from another planet. Previous sample return missions from the Moon and smaller bodies (asteroids and comets) did not face the challenge of escaping a planetary gravity well. The Sample Retrieval Lander will include a Mars Ascent Vehicle that will escape Mars' gravity, which is 40% that of Earth's, to carry the samples into Mars orbit.
- Partially autonomous on-orbit rendezvous and capture at Mars. The orbiting sample container is a small target for rendezvous in space.
- Robotic sample handing and sealing within a container whose exterior is free of martian dust, for planetary protection.
- First round-trip mission to another planet, a pathfinding demonstration for future human exploration.
- First return of samples from another planet. MSR will also involve backward planetary protection (preventing contamination of Earth's environment) for returned samples, as well as provide specific information necessary for astronaut safe operations that only laboratory analyses of samples, such as regolith, can provide.
- The most powerful electric propulsion system ever used for an interplanetary mission.

Some of these "firsts" were demonstrated in the exploration of the Moon by Apollo astronauts, but uncrewed operations on and around a planetary-size body involve new challenges. Moreover, some challenging tasks must be accomplished autonomously. These advances potentially apply to uncrewed missions to other planets beyond Mars.

MSR provides huge risk reduction for human missions, because hazards will be well known and solutions tested on a cargo that is more tolerant of surprises than human bodies. The return of samples from Mars will provide data that will inform NASA's Moon-to-Mars exploration strategy by characterizing the properties of key materials (such as regolith and dust) in the martian environment, validating the measures designed to protect the Earth from possible biological or inorganic contaminants on Mars, and informing the science to be conducted by human explorers. Characterization of the chemical composition, particle size and shape, toxicity, and electrical and magnetic properties of fine-grained materials on Mars can mitigate astronaut health and safety concerns resulting from exposure, and will be crucial in future mission design, operations, and resource considerations (21).

Some have advocated that we should just wait for humans to return samples, but that philosophy means putting off high-priority science for at least an extra decade and probably longer (given uncertainties surrounding a timeline for securing the funding for human exploration of Mars), and it does not account for the fact that the first several human missions may not go to optimum sampling locations for addressing critical scientific questions identified by the scientific community.

Why Is Jezero Crater a Compelling Sampling Site?

Admittedly, addressing planetary-scale scientific questions using samples from a single collection site conveys a certain hubris, but terrestrial geology and lunar exploration demonstrate that well-chosen sampling locations provide data of global significance. Jezero crater and its environs are especially promising for sampling to allow scientific advances.

The Jezero landing site was selected through a series of community workshops that evaluated candidate locations against the mission's science objectives (22). Those objectives encoded key characteristics important for MSR, notably that the mission should investigate an "astrobiologically relevant ancient environment, with geologic diversity" (23). The former reflects the centrality of seeking evidence of potential life on Mars and emphasizes rocks deposited in the distant past when the planet's climate was warmer and wetter, and therefore more habitable. The latter embraces the notion that different types of rocks are needed to address the many distinct scientific questions that motivate sample return (6).

Jezero is a 45 km-diameter crater in the Nili Fossae region (24). The ~3.9 billion-year-old crater was emplaced into even older (Noachian) crustal rocks including megabreccia from the nearby Isidis impact basin (25, 26). The key attraction of Jezero as a landing site is a ~40 km^2 sedimentary fan associated with an extensive canyon system that breaches the crater rim (24). Jezero crater once hosted a large lake, probably in Late Noachian to Early Hesperian time, i.e., ~3.6 to 3.8 billion years ago (24, 27–30). The sedimentary fan has been interpreted as a delta which exposes both lake- and river-deposited rocks (31). Given the potential habitability of an ancient martian lake, and the high biosignature preservation potential of a delta, Jezero clearly meets the astrobiological criterion for a sampling site. Indeed, rocks of similar age and broadly similar setting contain some of the earliest evidence for life on Earth (32).

Perseverance landed in Jezero on February 18, 2021, and as of this writing has operated on Mars for ~1,200 martian sols, investigating rocks of the crater floor, the sedimentary fan, and an enigmatic geologic feature abutting the inner crater rim called the Margin Unit. In recognition of the very distinct geologic environments in the crater (33), the mission has been executed in discrete investigation campaigns.

Perseverance landed on the crater floor about 2 km from a prominent scarp marking the edge of the sedimentary fan. The Crater Floor campaign (34, 35) confirmed the presence of two lithologic units seen from orbit (33). The first unit, now referred to as the Máaz formation, is an igneous lithology tentatively interpreted as a series of lava flows. The Máaz formation surrounds and overlies outcrops of the Séítah formation. Séítah rocks are also igneous, but they crystallized within a thick magma body in which crystal settling occurred. Máaz lavas appear to have flowed across antecedent topography developed on eroded Séítah rocks. It is unknown how much of the estimated ~1 km of crater fill (27, 36) consists of these or other igneous rocks. Both igneous units contain secondary minerals indicating some alteration by water.

A ~25 m thick sequence of sedimentary rocks exposed in the delta scarp was explored in the Delta Front campaign. These sandstones and mudstones are now termed the Shenandoah formation (37). The lowest exposed rocks are sandstones apparently deposited in a distal alluvial fan setting. Salt-rich mudstones overlie the sandstones, suggesting basin flooding and a transition to a saline lake setting. The mudstones are in turn overlain by steeply dipping sandstones and pebble conglomerates likely deposited as a river delta advanced into the basin. The delta scarp also exposes lens-shaped bodies of meter-scale boulders, interpreted as flood deposits (30).

The Upper Fan Campaign was undertaken on a traverse across the fan surface. Curvilinear features observed from orbit are interpreted as fluvial deposits (31). *Perseverance* confirmed these features are sandstones, likely deposited in rivers atop the prograding delta. The curvilinear sandstones are overlain by a younger generation of sandstones and conglomerates that define the lobate structures on the fan surface. A widespread boulder unit often caps the fan, possibly associated with the boulder lenses exposed on the delta front.

In its most recent campaign exploring the Margin Unit, *Perseverance* discovered rocks rich in carbonate, silica, and sometimes olivine. This assemblage suggests aqueous alteration of olivine, but the origin of the rock—whether sedimentary or igneous—remains uncertain (38). At the completion of this campaign, the rover may traverse southeastward up the rim toward Nili Planum.

Many of the rocks exposed on the crater rim and Nili Planum are much older than those already investigated, and are of fundamentally different origin. Interesting exploration targets include outcrops interpreted as megabreccia, possibly derived from deep within the planet by the 4.0 billion-year-old impact that created the Isidis basin (26). By analogy to terrestrial impact craters, the Jezero rim may expose an impact-induced hydrothermal system—a potentially habitable environment very different from the lake and river system from which samples have already been obtained. Samples of these rocks would significantly enhance the science value of the existing *Perseverance* collection.

Thus far in the mission *Perseverance* has acquired 15 unique rock samples for potential Earth return. These include igneous rocks, critical for deciphering the geochemical evolution of early Mars and for radiometric dating, and sedimentary rocks and chemical precipitates of great interest for investigating surface paleoenvironments, habitability, and the possibility of ancient martian life. The *Perseverance* sample collection, which also includes regolith and atmosphere samples, is of very high value for addressing diverse questions about Mars and beyond (19).

Why Are Observations and Analyses of Samples in Laboratories on Earth Required, and How Do They Relate to Robotic Exploration?

Many of the scientific questions that motivate MSR require observations and analyses of greater sensitivity and resolution than can be obtained by remote-sensing instruments. To illustrate, we offer two specific examples.

The detection and characterization of organic compounds that may indicate the former presence of living organisms is one critical objective of MSR. The demonstrated detection limit for amino acids (including chirality) and nucleobases in samples (in this case, martian meteorites) analyzed in the laboratory is approximately 0.1 to 1.0 parts-per-billion (39). This is driven mostly by procedural blanks in the laboratory, rather than instrument sensitivity. Such low detection limits cannot be achieved by rover in situ measurements. Amino acids would have to be at parts-per-million levels to be detected by the Gas Chromatograph Mass Spectrometer instrument on the *Curiosity* rover (40, 41), and measurement of chirality is not possible.

Quantifying Mars' geochronology by measuring the crystallization ages of igneous rocks using radiogenic isotopes is another important objective of MSR. These ages can be used to calibrate geochronologic models for Mars and other planets. On Earth, various radiogenic systems (^{40}K-^{40}Ar, ^{87}Rb-^{87}Sr, ^{147}Sm-^{143}Nd, ^{176}Lu-^{176}Hf, ^{238}U-^{207}Pb, ^{232}Th-^{208}Pb, and others) are commonly used, and consistent ages measured by more than one system add confidence. For ancient rocks billions of years old, these various systems can have analytical uncertainties of ±25 to 50 My (42). For comparison, the only in situ measurement so far, a K-Ar age of a 4.2 billion-year-old rock on Mars by the *Curiosity* rover, had an uncertainty of ±350 My (43). The only other remote-sensing chronometer being developed for spacecraft employs the Rb-Sr isotope system. A prototype laboratory version used to analyze the age of a young (~170 My-old) martian meteorite has an uncertainty of ±20 My (44), consistent with ages determined terrestrial laboratories though much less precise. Analytical uncertainty for older rocks would be greater.

These two examples bolster the argument that analyses of returned samples may be the only way to address unambiguously some critical science questions. We also note that there are many kinds of observations and measurements that cannot be made by remote sensing at all.

However, there are important synergies between MSR and the robotic missions of the Mars Exploration Program. Since the pioneering Viking missions, we have collected three decades' worth of data covering Mars at virtually every wavelength possible from orbit and local in situ data from the surface and subsurface at a handful of sites. The data from these orbiters and landers, and models based on them, led to the selection of Jezero crater as the sampling site for MSR because the diverse geologic units there will address many different scientific hypotheses about Mars (20). But MSR samples also will provide ground truth for predictions about the geology and age of the Jezero region units and, in perhaps many cases, reinterpretation of data collected at Jezero, at other sites, and globally. Understanding what we got right, what we got wrong, and what we missed entirely will guide the scientific questions to be addressed next at Mars through new research and flight missions. The ability to ground truth our data will usher in a new wave of technology and instrument development and help determine the prioritization and capabilities of payloads and spacecraft for the next generation of missions.

What Critical Science Questions Will Mars Samples Address?

We will consider the scientific value of returned Mars samples by identifying some overarching unanswered questions that could be addressed (6, 45). Such investigations can now be considered in more depth, because we have information on the specific kinds of samples that have been preliminarily characterized in situ by *Perseverance* rover instruments (34, 46–48) and cached for return to Earth. The returned samples will uniquely illuminate the early history of Mars (Jezero samples are older than almost all martian meteorites), extend compositional diversity (sedimentary rocks and chemical precipitates are not represented in the meteorite collection), decrease the observational scale (observations and measurements made from orbit and from rovers are coarse in comparison to those that can be made on rock samples), and provide definitive answers to questions which cannot be adequately addressed with meteorites and spacecraft observations.

Did Ancient Extraterrestrial Life Exist in the Solar System? If So, When, Where, and What Were Its Attributes? Possibly the most profound question that will be asked when samples are returned is how do we look for life that may be different from our own? Fundamentally, what is life and what record does it leave? This problem is likely to engage a broad intellectual community beyond those in planetary science.

The challenge in life detection is not just to be able to detect relatively obvious life forms, but to utilize instruments having the sensitivity and resolution to measure faint signatures as unambiguously as possible. Life detection is also a stepped process in which the result of one measurement determines what follows. MSR allows us to use the entirety of Earth's laboratory capabilities, optimizing the chances of detecting and correctly interpreting subtle signals. Fine-grained sedimentary samples from the lower delta contain clays and sulfates and are most likely to preserve any possible evidence for ancient life (49). Also, sedimentary rocks containing abundant silica and carbonates collected from the Margin Unit may preserve biosignatures.

Uniquely establishing evidence for extinct life can be especially challenging, of necessity involving a combination of field and laboratory studies to document habitability, to assess the preservation potential for biosignatures, and to document the absence of contamination (50, 51). Laboratory investigations require organic extraction protocols and molecular/stable isotopic characterizations that are only possible in terrestrial settings (52). Investigation pathways can be discovery-dependent, as new information dictates downstream experiments. The discovery of ancient life on Mars would allow us to test assumptions about universal requirements for life, and possibly uncover novel ways in which life processes are carried out.

How and Where Did Prebiotic Organic Chemicals Form, and What Role Did They Play in Establishing the Required Chemical Context for the Origin of Life? One necessary condition for life's origin (in addition to water and a source of energy) is the availability of appropriate organic compounds. We have very little knowledge of diagnostic organic signatures for Earth's earliest primitive life forms, because the rock record no longer exists. However, the ancient organic record of Mars may be better preserved, as suggested from studies of martian meteorites (53) and analyses by rovers (54). Sedimentary samples that have been carefully selected by *Perseverance* rover team scientists on the basis of their potential to acquire and preserve organic matter, as opposed to random samples launched as meteorites, may allow a much better opportunity to understand the full complexity of prebiotic chemistry. The molecular, chiral, and stable isotopic properties of organic matter from Mars rocks can be compared with primitive meteorites and cosmic dust to provide information on the role of prebiotic chemistry throughout the Solar System.

What Is the History of Habitable Environments on Planets beyond Earth? Defining planetary habitability requires information on the timing of accretion, stellar and impact fluxes, and orbital stability, as well as the role of bulk composition versus size in setting pathways for magmatic, tectonic, magnetic, and atmospheric evolution. Within our Solar System, Mars exclusively preserves the ancient geologic record needed to understand the early evolution of habitability (55).

Five geologic environments are presently recognized as potentially habitable and capable of preserving evidence of habitation (56): sedimentary systems; hydrothermal systems; deep groundwater systems; locations that experienced water/rock/atmosphere interactions; and iron-rich springs. Jezero crater contains an ancient sedimentary system of lakebed and deltaic deposits, and basement rocks in large craters (accessible as samples from the Jezero crater rim) are commonly affected by hydrothermal fluids. Volcanic rocks sampled in Jezero are less likely to serve as a habitable environment, but to the extent that they have undergone aqueous alteration, they may contain traces of life. The *Perseverance* rover is addressing how the environmental conditions arose and evolved over time, but returned samples will provide evidence necessary to definitively establish the conditions that may have led to the onset of habitability, as well as its duration, in multiple environments.

How Did the Planets Form, Differentiate, and Evolve as Geological and Geophysical Bodies? Much of what we surmise about Mars' geologic evolution and internal composition comes from martian igneous meteorites (12, 13), which have very limited variations in formation age and chemical composition. Analyses of igneous rocks by rovers indicate a less biased and more inclusive view of Mars igneous rock ages and compositions (14, 57, 58). The samples collected in Jezero crater include ancient basaltic and ultramafic rocks that will provide a thermochemical record of the planet not presently available and serve as a new window on its interior. Their trace element and radiogenic isotopic abundances will allow insights into the differentiation of mantle and core, as well as address fundamental questions about the evolution of Mars magmatic activity through time. Radiogenic isotopes in igneous rocks from the crater floor and rim, as well as units outside the crater (59) if sampled, will constrain the evolutionary timeline for Mars and, by tying them to specific geologic units with measured relative ages, will serve as calibration points for assigning absolute ages to crater-density distributions. Petrologic analyses will provide the necessary context for interpretation of radiometric ages. Paleomagnetism studies of oriented igneous samples in Earth-based laboratories (60) can reveal the history of the planetary dynamo, constrain the present model of mantle convection, and test hypotheses that loss of the dynamo facilitated climate change.

Laboratory studies of the mineralogy, texture, geochemistry, and stable isotope composition of returned sedimentary rocks will provide information on provenance and diversity of crustal rocks, absolute ages, history of water, and evolution of climate at this Noachian site. The stratigraphic context of the collected sedimentary samples provided by *Perseverance's* investigation is important in understanding changes in this habitable environment.

Can We Use Early Geologic and Geochemical Records throughout the Solar System to Interpret How Planetary Growth and Dynamics Controlled or Altered the Distribution of Planets and Planetesimals during Its First Billion Years? Nucleosynthetic isotope anomalies in meteorites and planetary samples indicate distinct reservoirs in the early Solar System (61), hypothesized to have been separated by the rapid growth of Jupiter. Analyses of these isotopes in igneous rocks can only be done in terrestrial laboratories.

Instabilities in the motions of giant planets in the first billion years may have scattered planetesimals, profoundly affecting the impact records of planets (62). Major questions remain about the timing and duration of large impacts, suggesting that the "Late Heavy Bombardment" may not have been a spiked or singular even (63). The ages of one or more impact events on Mars can potentially be quantified by radiogenic isotope analyses of returned samples such as megabreccia. Although the shock states of cached samples are unknown, it seems likely that most surface samples have been affected by impacts, and ejecta from large impacts may have been added to the landing site and may be present in regolith samples. Any information on early collisions at Mars' orbital position would help us understand the dynamics of early Solar System bodies as a whole.

How Did Planetary Atmospheres Form and Evolve, and What Are the Processes That Caused Them to End Up in Such Different States? The scientific value of a returned atmospheric sample has been described repeatedly (64, 65). Returned samples will include not only the modern atmosphere (as a dedicated sample or in several witness tubes that are mostly air, and as headspace gas in sample collection tubes), but also trapped ancient atmospheric gases in solid igneous samples or in fluid inclusions. The returned atmospheric samples may constitute half a micromole of gas—an abundance for noble gas analyses but not so much for uncommon isotopes of nitrogen and oxygen. Major and trace element abundances and isotopic compositions will provide constraints on the origin and evolution of the atmosphere, with possible implications for climate change. The amounts of species in low abundance can reveal information on the hydrologic cycle. The isotopic compositions of gases, such as helium and argon, in basalts that have been sampled in Jezero crater also have the potential to reveal details about the evolution and degassing of their mantle source regions. The methane isotopic composition can reveal whether this compound formed inorganically or biologically—methane isotopes in the atmospheric sample cannot be measured with current instruments, but will likely be analyzed as analytical technology advances. Understanding how the atmosphere has evolved is critical to constraining the martian volatile inventory and discerning how volatile species were originally acquired and have interacted over time with the planet. This information will play a significant role in comparison studies of other planets with atmospheres, such as Earth, Venus, and exoplanets.

Conclusions

MSR, as repeatedly advocated by the planetary science and astrobiology communities, will address critical science questions in ways that only analyses made in terrestrial laboratories can do. Carefully chosen rock samples, as well as samples of the regolith and atmosphere, have been collected by the *Perseverance* rover in Jezero crater. Besides their value to science, returned Mars samples will develop technological capabilities and provide information needed for future human exploration, as well as demonstrate the Nation's continued leadership in the peaceful exploration of space.

Data, Materials, and Software Availability. There are no data underlying this work.

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