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Sampling Mars: Geologic context and preliminary characterization of samples collected by the NASA Mars 2020 Perseverance Rover Mission

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The NASA Mars 2020 Perseverance Rover Mission has collected samples of rock, regolith, and atmosphere within the Noachian-aged Jezero Crater, once the site of a delta-lake system with a high potential for habitability and biosignature preservation. Between sols 109 and 1,088 of the mission, 27 sample tubes have been sealed, including witness tubes. Each sealed sample tube has been collected along with detailed documentation provided by the Perseverance instrument payload, preserving geological and environmental context. Samples representative of the stratigraphy within each of four campaigns have been collected: samples from the Crater Floor Campaign represent a suite of potentially petrogenetically related igneous rocks displaying variable degrees of aqueous alteration; samples from the Fan Front record fluvial to deltaic sediments formed by the transport and deposition of materials from the Jezero watershed; regolith samples from the Fan Front preserve material possibly representative of global dust as well as diverse, locally derived clasts; Upper Fan samples record the latest stages of aqueous activity within Jezero; and samples from the Margin Campaign preserve lacustrine, littoral, or possibly igneous processes that may have occurred early in the history of the crater. Along with anticipated samples from the older rocks within the rim of Jezero Crater, Perseverance promises to deliver a suite of samples preserving a diversity of formation environments and ages. Upon return to Earth and analysis in terrestrial laboratories, these samples would address longstanding questions pertaining to the geologic evolution of Mars, its habitability, and the potential for life outside the Earth.

Mars | Jezero Crater | sample return | geology

Significance

The NASA Perseverance Rover has collected numerous sealed sample tubes containing rock, regolith, and atmosphere that represent the different rock types encountered within Jezero Crater, Mars. Analysis of these samples in laboratories on Earth would enable fundamental questions to be addressed, including how Mars formed, its geologic evolution, and whether Mars ever hosted life.

A primary goal of the NASA Mars 2020 Perseverance rover mission is to select, acquire, and document a scientifically return-worthy collection of martian samples for return to Earth by future missions (1). To achieve this task, the rover is equipped with an integrated suite of science instruments that operate together as part of a mobile sampling platform. Data from remote sensing instruments mounted on a pan/tilt mast and proximity instruments mounted on a robotic arm provide detailed contextual information for each sample (*Materials and Methods*).

Mars Sample Return (MSR) has been a high priority of the scientific community for decades (McSween, (2); McCubbin, (3)). Detailed analyses in Earth-based laboratories of carefully documented martian samples collected from regions with known geologic contexts will be essential for addressing the highest-priority science questions relating to Mars (4). These questions include those about the geologic history of Mars, particularly the role of water, the evolution of volatiles and climate on Mars, the timeline of planetary scale processes, and the potential biological history of Mars (5).

Perseverance is currently exploring the Noachian-aged Jezero Crater, once the site of a delta-lake system with a high potential for habitability and biosignature preservation. The rover carried 38 identical sample tubes designed for rock core or regolith samples and five witness tube assemblies ("witness blanks") for characterizing contamination from the rover. At the time of writing, 24 of 38 sample tubes have been sealed, as have 3 of the witness tubes (Table 1). Of these, nine sample tubes (seven containing rock cores, one containing regolith, and one filled with Mars atmosphere) and 1 witness tube have been deposited at the Three Forks depot in Jezero Crater, while the rest are being carried onboard Perseverance. The orientations of all rock core samples have been estimated relative to martian geographic coordinates to enable their records of geological and geophysical processes to be oriented at the time they formed and/or were altered (Weiss et al. (6)).

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Table 1. List of samples collected by the Perseverance Rover

#	Sample designation[*]	Location of collection	Type (Fm[†])	Notes	Current location[‡]
1	M2020-109-1 *WB-1*		Witness Blank	Pre-launch exposure	Perseverance
Crater Floor Campaign					
2	M2020-164-2 *Roubion*	Séítah "Thumb"	Atmosphere[§]	Polygonal low-lying outcrop within Máaz formation	Three Forks
3	M2020-190-3 *Montdenier*	Rochette target, Artuby Ridge	Igneous (Máaz fm.)	Float associated with ridge	Three Forks
4	M2020-196-4 *Montagnac*	*Same as Montdenier*			Perseverance
5	M2020-262-5 *Salette*	Brac outcrop within Séítah South	Igneous (Séítah fm.)	Outcrop. Low-lying, layered	Perseverance
6	M2020-271-6 *Coulettes*	*Same as Salette*			Three Forks
7	M2020-298-7 *Robine*	Issole outcrop within Séítah South	Igneous (Séítah fm.)	Outcrop. Ridge, layered, resistant	Perseverance
8	M2020-337-8 *Malay*	*Same as Robine*			Three Forks
9	M2020-371-9 *Hahonih*	Sid target	Igneous (Máaz fm.)	Float associated with massive, blocky rocks	Perseverance
10	M2020-377-10 *Atsah*	*Same as Hahonih*			Three Forks
Fan Front Campaign					
11	M2020-490-11 *Swift Run*	Skinner Ridge outcrop, Hawksbill Gap	Sedimentary (Shenandoah fm.)	Outcrop. Horizontally-layered, medium-grained, resistant	Perseverance
12	M2020-495-12 *Skyland*	*Same as Swift Run*			Three Forks
13	M2020-499-18 *WB2*		Witness Blank		Perseverance
14	M2020-509-14 *Hazeltop*	Wildcat Ridge outcrop, Hawksbill Gap	Sedimentary (Shenandoah fm.)	Outcrop. Horizontally-layered, fine-grained, recessive	Perseverance
15	M2020-516-15 *Bearwallow*	*Same as Hazeltop*			Three Forks
16	M2020-575-16 *Shuyak*	Amalik outcrop, Cape Nukshak	Sedimentary (Shenandoah fm.)	Outcrop. Horizontally-layered, fine-grained, recessive	Perseverance
17	M2020-579-17 *Mageik*	*Same as Shuyak*			Three Forks
18	M2020-584-18 *WB3*		Witness Blank		Three Forks
19	M2020-623-19 *Kukaklek*	Hidden Harbor outcrop, Cape Nukshak	Sedimentary (Shenandoah fm.)	Outcrop. Horizontally-layered, fine-grained, recessive	Perseverance
20	M2020-634-20 *Atmo Mountain*	Observation Mountain, Cape Nukshak	Regolith	Megaripple	Perseverance
21	M2020-639-21 *Crosswind Lake*	*Same as Atmo Mountain*			Three Forks
Upper Fan Campaign					
22	M2020-749-22 *Melyn*	Berea outcrop	Sedimentary (Tenby fm.)	Outcrop. Alternating dm-scale resistant sandstone and recessive coarser-grained layers	Perseverance
23	M2020-822-23 *Otis Peak*	Onahu outcrop	Sedimentary (Otis Peak fm.)	Outcrop. Cross-stratified conglomerate, resistant	Perseverance
24	M2020-882-24 *Pilot Mountain*	Dream Lake outcrop	Sedimentary (Otis Peak fm.)	Outcrop. Low-lying, medium-grained, recessive	Perseverance
Margin Campaign (ongoing)					
25	M2020-923-25 *Pelican Point*	Hans Amundsen M.W. within Mandu Wall	Sedimentary (TBD fm.)	Outcrop. Minimally-layered, low-lying, medium- to coarse-granular, recessive	Perseverance
26	M2020-949-26 *Lefroy Bay*	Turquoise Bay within Mandu Wall	Sedimentary (TBD fm.)	Outcrop. Minimally-layered, low-lying, medium- to coarse-granular, recessive	Perseverance
27	M2020-1088-27 *Comet Geyser*	Bunsen Peak	Sedimentary	Probable outcrop. Resistant, massive	Perseverance

Notes: Images of rock and regolith cores are shown in Fig. 5.
[*]Date and order of collection is encoded in the sample designation, e.g., M2020-164-2 was collected on sol 164 of the mission, and was the second sample collected
[†]Fm = formation, where applicable
[‡]Denotes whether the sample is currently onboard the *Perseverance* rover, or at the Three Forks sample depot. Total numbers in each location: 10 tubes at Three Forks, 17 tubes onboard *Perseverance*.
[§]No sample retained in the coring tube; contains ~4.9 μmol of martian atmosphere, collected at L_S = 81.87 and an ambient temperature of 221 K (4, 7).

Once a sampling target has been identified, each sample is documented by a standardized set of required activities and observations. These activities are called the Standardized Observation Protocol, or STOP list. The STOP list includes imagery at multiple scales and resolutions, together with chemical and mineralogical analyses ("proximity science") of the outcrop surface (e.g., ref. 7). An ~1 cm deep and 5 cm diameter abrasion target is acquired within a few tens of centimeters of the sample target, within the same lithology or sedimentary layer, in order to provide a fresh rock surface for proximity science. In this "sample proxy" abraded patch, high-resolution images and detailed maps of elemental composition, mineralogy, and potential organic matter are obtained. After coring, an image is taken of the sample in the tube, the amount of sample is estimated, and the tube is hermetically sealed (8). Unique serial numbers are readily visible on the tube and seal exteriors to ensure unambiguous identification even decades after acquisition.

Sample documentation comprises a Sample Dossier and an Initial Report; these are uploaded to the NASA Planetary Data System

(PDS) on a regular (6-mo) cadence. The Sample Dossier contains all observations from the STOP list, along with relevant rover data (e.g., temperatures, rover location, rover arm position and actions, etc.) at the time of sampling. The Sample Dossier primarily consists of pointers to the relevant instrument-specific and engineering data products, which are also available on the PDS. Thus, the dossier acts as a "one-stop shop" for sample-specific results. The Initial Report consists of a description of each sample in a standardized narrative format that is written by Returned Sample Science Participating Scientists and the Science Team within three weeks of sample acquisition. Initial Reports capture the rationale for sampling and describe the interpretations available at the time of sampling and the completion of the STOP list. The Initial Report can be thought of as a set of field notes associated with each sample; in this way, they are perhaps the most accessible types of sample documentation for the community. However, like field notes, the Initial Reports do not include extensive assessment or interpretation of the collected samples; these are reported elsewhere, primarily within the peer-reviewed literature.

In parallel with these observations, the MEDA weather station has been used to study the local, present-day environment and to estimate the amount of gas in the headspace of each sealed sample and witness tube—an estimated total of 44.3 μmoles of martian atmospheric gas [a preliminary MSR study estimated that the atmospheric sample needed to implement volatile studies should be at least 19 μmoles (9)]. Results from MEDA suggest that the present-day environmental conditions at Jezero allow for a diurnal atmospheric-surface water exchange of 0.5 to 10 g water per m^2 (10). This water can hydrate the sulfates, chlorides, and perchlorates and the occasional formation of frost at Jezero crater. However, the environmental conditions at the surface of Jezero Crater, and within the sealed samples, are incompatible with the cell replication limits currently known on Earth (10).

At the time of writing, Perseverance has completed three campaigns—the Crater Floor, Fan Front, and Upper Fan—and is in the midst of the Margin Unit campaign (Fig. 1). The purpose of this contribution is to provide an overview of the samples collected to date during each campaign, including their mineralogy and petrology from rover-based investigations, and their potential returned sample science, if and when the samples are returned to Earth and analyzed in laboratories. Sources of information for this review include the peer-reviewed literature, as well as Initial Reports for the most recently collected samples.

Crater Floor Campaign Samples

Geological Context. The first rock samples collected by the Mars 2020 mission represent units exposed on the Jezero Crater floor, from the potentially oldest Séítah formation outcrops to the younger rocks of the heavily cratered Máaz formation (Fig. 2). The Máaz formation had previously been mapped as the Crater floor fractured rough unit (Cf-fr), and the Séítah formation as the Crater floor fractured unit (Cf-f-1) by Stack et al. (11). Proximal and remote analyses carried out during the campaign suggest that all crater floor outcrops investigated are igneous in origin and dominantly ultramafic to mafic in composition (12–14). Surface investigations further reveal landscape-to-microscopic textural, mineralogical, and geochemical evidence that these crater floor units were likely emplaced as lava flows; furthermore, these rocks exhibit variable amounts of aqueous alteration and the formation of secondary carbonate and sulfate phases, among others (12–20). The Máaz formation is a widespread extrusive unit that exhibits a smooth morphology lower in the stratigraphy, and a rougher, more massive, rubbly, and cratered morphology upsection (19, 21). The sample cores *Montdenier* and *Montagnac* are representative of the lower Máaz members, which are more mafic and pyroxene-dominated. In contrast, the upper Máaz members—represented by the *Hahonih* and *Atsah* sample cores—are more silicic and plagioclase-dominated. Taken as a whole, the Máaz formation provides important stratigraphic and geochronological constraints for the other major geological units in Jezero crater (19, 22), including the underlying Séítah formation and the overlying strata of the Jezero delta.

On the crater floor, the Máaz formation overlies the Séítah formation, which, morphologically, comprises an irregular eroded region of the crater floor consisting of NE-SW-trending ridges surrounded by megaripples, loose rocks, and boulders; it is largely devoid of craters. Outcrop exposures of the Séítah formation are composed of coarse-grained, thickly bedded, and tabular layers interpreted to represent layering of an olivine-dominated cumulate likely originating within a thick lava flow, laccolith, or lava lake on the crater floor (13). The sample cores *Robine* and *Malay* were collected near the boundary with the Máaz formation, toward the southernmost exposure of Séítah, while sample cores *Salette* and *Coulettes* were collected further into the unit. The eight core samples collected from the Jezero crater floor represent four "double-sampled" outcrop exposures—two of Máaz and two of Séítah—that are all interpreted to be stratigraphically below (i.e., older than) the western fan sediments (23).

All crater floor samples contain major igneous rock-forming minerals such as pyroxene, olivine, and feldspar, accessory minerals including oxides and phosphates, and evidence for various degrees of aqueous activity in the form of water-soluble salt, carbonate, sulfate, iron oxide, and iron silicate minerals (7, 12, 24). The natural surfaces of the Máaz formation exhibit fine-grained textures with occasional millimeter-sized grains. Abraded surfaces show holocrystalline, equigranular to porphyritic igneous textures. Some Máaz formation flow layers and surfaces contain millimeter- to centimeter-sized irregular to circular voids or pits (e.g., ref. 16). The primary mineralogy is dominated by Fe-rich pyroxene and plagioclase and the Máaz formation contains some of the lowest Mg contents reported for martian magmatic rocks (16). On abraded surfaces, secondary minerals appear to line the edges of the voids or pits, and in some cases completely fill voids or replace grains (e.g., the *Guillaumes* abrasion patch; 4). Secondary minerals include hydrated Mg-sulfate-anhydrite-perchlorate grain mixtures, pervasive reddish-brown staining, and rare carbonate (15, 20, 24). The Séítah formation exposures are mainly composed of coarse-grained olivine (12, 13, 25). On natural surfaces these 2 to 3 mm diameter dark gray to green olivine grains appear densely packed (14, 18). On abraded surfaces, a granular texture of both olivine and pyroxene grains can be seen. PIXL X-ray fluorescence maps of the abraded patches reveal that the olivine has a uniform composition (~Fo_{55}) making up ~60 to 70 vol% of the rock, evidence of large interstitial augite grains (exhibiting a poikilitic texture), and fine-grained Al-rich crystalline mesostasis with Na- and K-rich feldspars, Fe-Cr-Ti oxides, and Ca-phosphates (13). Compositional and textural evidence exists for some dissolution of olivine, but much less than typically observed in terrestrial olivine-rich lithologies (25). Likewise, the areas of mesostasis show few signs of secondary salts (13). The secondary mineralogy in the Séítah formation is similar to that observed in the Máaz formation rocks and includes hydrated Mg-sulfates, anhydrite, and possible perchlorates, although carbonate appears to be more abundant (15, 20, 24, 25).

Potential Returned Sample Science. Following sample return, the compositions and ages of the variably altered igneous rocks collected from the Jezero crater floor would be expected to reveal the geophysical and geochemical characteristics of the planet's interior at the time of emplacement, enabling comparison with

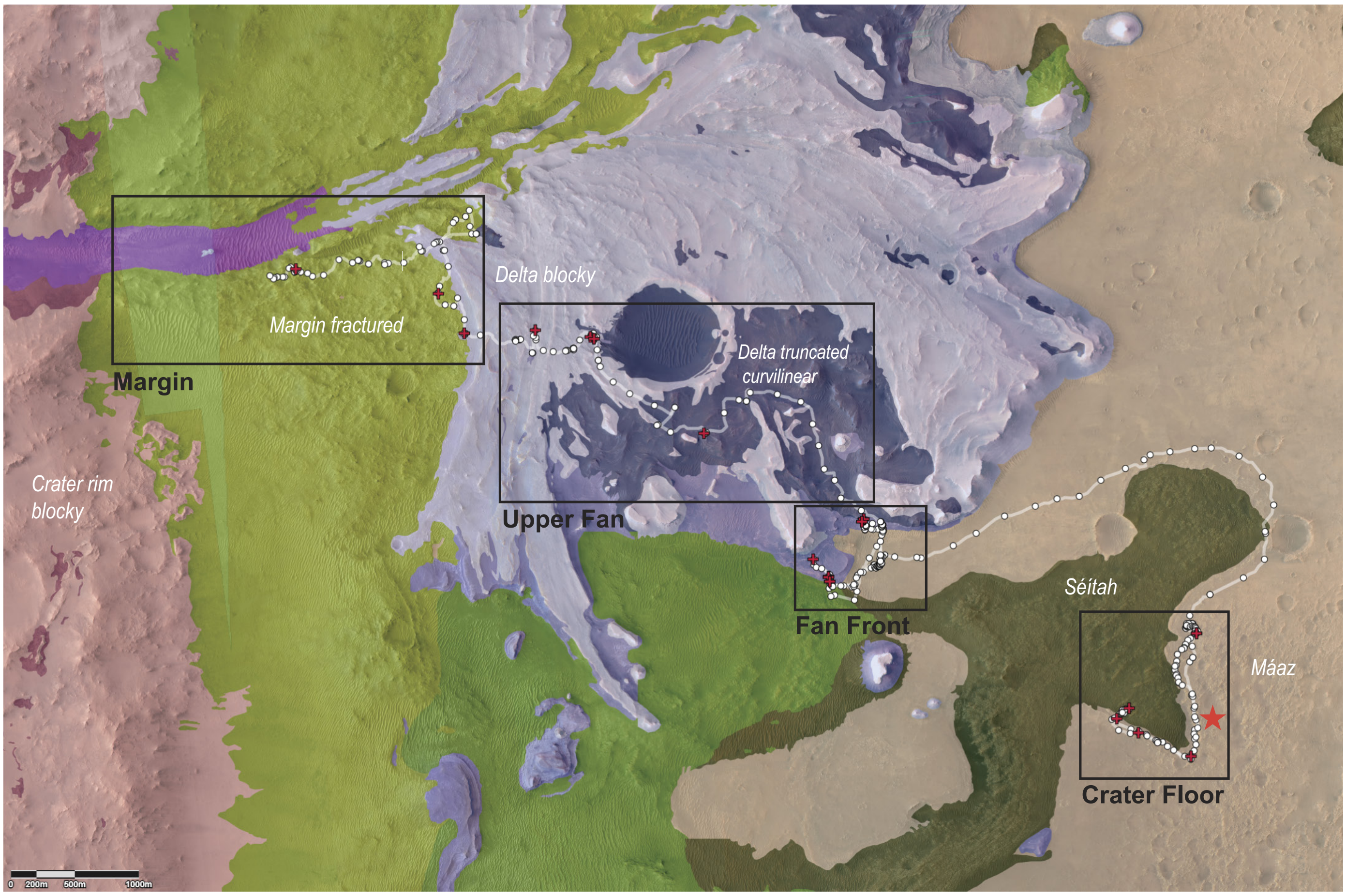

Fig. 1. Map showing mission progress at the time of writing, superimposed on a geologic map of Jezero crater, after ref. 11. Rover traverse and waypoints shown with white line and dots, respectively; sampling locations shown with red crosses. Labeled black boxes show approximate extent of each campaign. Names of major units or formations encountered—or expected to be encountered—are labeled in white italics. Approximate location of images shown in Fig. 2 are denoted with a red star.

other igneous rock compositions from other parts of Mars and from meteorites, helping to characterize martian magmatism, and placing timing constraints on geologic processes, both in Jezero Crater and more widely on Mars (5, 7). Geochronological analyses would provide critical constraints on the timing of events in Jezero crater, including the emplacement of the crater floor as well as potentially the onset of lake activity (7). The complex history of the crater floor (26) provides a challenge for achieving the goal of constraining the absolute chronology of Mars (5); however, only with sample analysis in terrestrial laboratories can the absolute and relative ages of events recorded within them be reconciled with the Máaz formation's erosional, burial, and exhumation history. Further to this point, petrographic observations and geochemical analyses, coupled with geochronology of secondary minerals, would reveal the timing and characteristics of aqueous activity while constraining the chemical and physical conditions of the environments in which these minerals precipitated. Understanding the nature, chemistry, and mechanisms of water–rock interactions at the microscale may help to establish whether habitable microniches, for example, potential endolithic habitats, were ever present in the crater floor sequences. High-sensitivity and high-resolution terrestrial laboratory analyses would also be crucial to determine the nature and composition of any organic compounds preserved in association with these phases (15, 27). Evidence for near-surface secondary alteration processes, requiring (sub)micron-scale measurements, will thus be key to constraining the style and duration of aqueous activity in Jezero Crater, past habitability, and cycling of organic elements in Jezero Crater.

Fan Front Campaign Rock Samples

Geological Context. Sedimentary rocks in the western sedimentary fan in Jezero crater were major targets for exploration and sampling by Perseverance because of their potential to record past fluvial and lacustrine environments, habitable conditions, and potential biosignatures (1, 28); this was one of the main factors in the selection of the Jezero crater landing site (29, 30). The oldest such rocks are found at the base of the eroded fan front, which exposes a sequence of sedimentary rocks totaling ~65 m in thickness. The mission team explored this area for more than one Earth year during the Fan Front Campaign, during which seven rock samples were collected (Table 1). Primary lithologies or features of interest during this campaign included indicators of past habitable environments and climate conditions, such as fluvial, lacustrine, and deltaic deposits and minerals precipitated in solution; rocks that can assist in constraining the timing and duration of aqueous activity; and rocks that can provide optimal conditions for biosignature preservation and may therefore be instrumental in the search for potential traces of life (28). The initial sampling plan for the fan front included two cores of fine-grained and clay-rich bedrock and two coarser-grained sedimentary rocks, one from a stratigraphically high site and one from a stratigraphically low site. Fine-grained sedimentary rocks are generally associated with an increased likelihood of preserving organic materials and other potential biosignatures and would thus have a higher astrobiological potential, whereas the coarser-grained samples would enable constraining the timing of the aqueous activity in the fan. Oriented bedrock samples were collected from

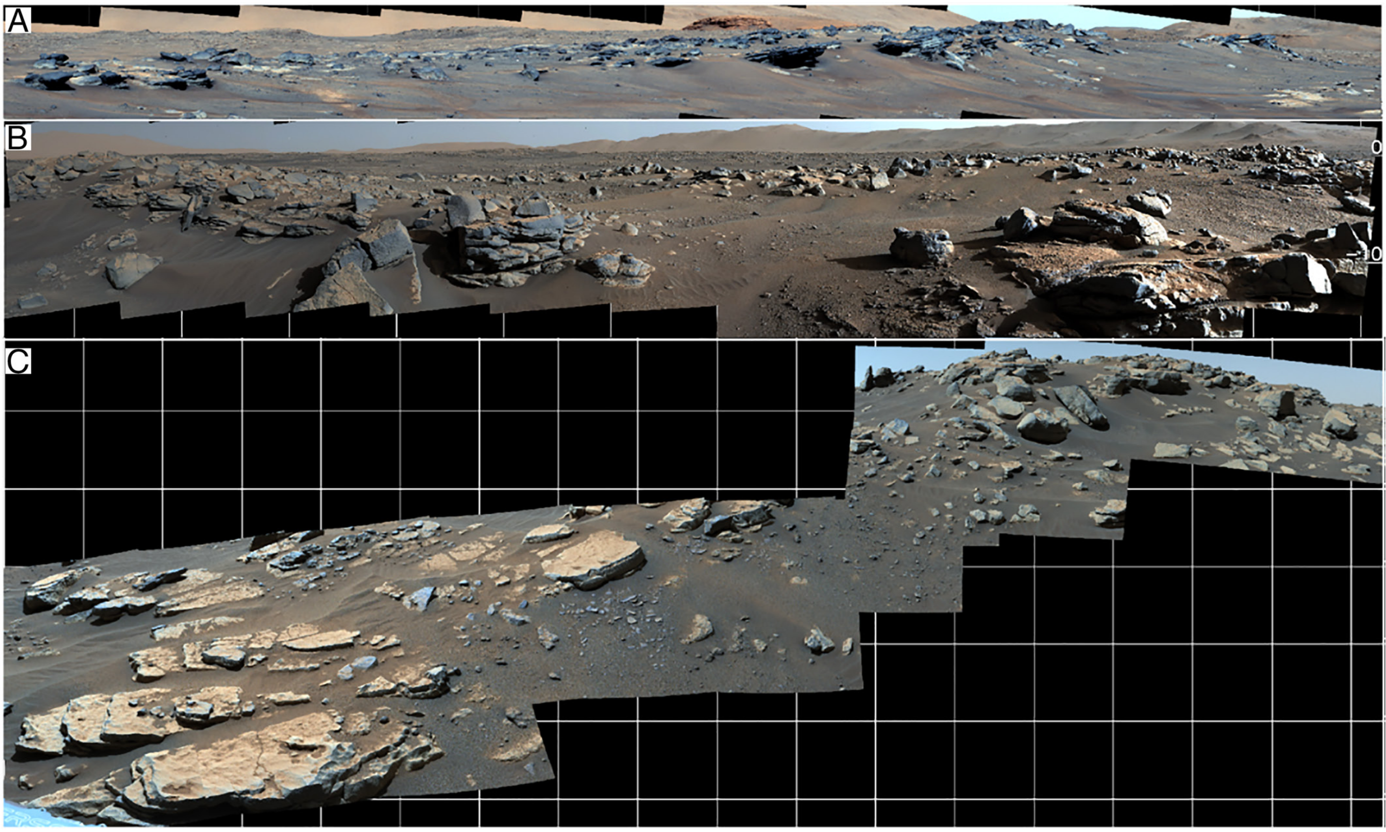

Fig. 2. Images showing the local contexts of Crater Floor samples: (*A*) 2 to 3 m tall cliff exposures of widespread Máaz formation that locally define the NW-SE trending Artuby Ridge. Kodiak mesa sediments that lie stratigraphically above can be seen in the distance. Boundary with southern edge of Séítah formation lies to the *Right* side of image. (*B*) Layering in lower Máaz formation outcrops near southern and eastern side of Séítah. Bouldery, crater-retaining, upper Máaz formation outcrops can be seen in the distance. (*C*) Tabular ~10 cm thick beds of Séítah formation (*Left*) grade into more massive, but still locally layered Séítah formation outcrops (*Right*).

throughout the stratigraphy with the objective of reconstructing aspects of the paleodepositional ecosystem and planetary evolution throughout this period of sedimentary deposition. The set of samples collected at the fan front comprises the first and oldest aqueously deposited sedimentary rocks that can be returned to Earth for future analyses, filling a total of nine tubes with four duplicate samples and one singleton; four of the duplicate samples were placed in the Three Forks Cache in early 2023 (Table 1).

Remote (Mastcam-Z, SuperCam) and proximity (PIXL, SHERLOC, WATSON) payload science instruments provided structural, textural, and chemical evidence for both the aqueous deposition and aqueous alteration of the rocks in the Fan Front, and enabled these rocks to be placed in a stratigraphic sequence of fluvial to lacustrine and overlying deltaic deposits (31). The cores *Shuyak* and *Mageik* were collected from flat, laminated, fine-grained sandstones interpreted as fluvial (31) (Fig. 3). These grainstones contain detrital igneous minerals such as olivine and pyroxene and layers that appear to concentrate heavy detrital minerals such as chromite, ilmenite, and zircon or baddeleyite (32). The rocks are hydrated, containing serpentine-like minerals (31, 33) and aqueously precipitated sulfates and carbonates (28, 31, 34, 35).

The light-toned mudstones/siltstones and sandstones along the fan front are interpreted either as lacustrine deposits (31), or as subaerial deposits of transported sulfate mineral grains (35). The matrix of the siltstone/mudstone *Hogwallow Flats* outcrop (from which the *Hazeltop* and *Bearwallow* samples were collected) is composed of fine-grained magnesium and ferrous iron clays and very soluble, aqueously precipitated and hydrated magnesium and ferrous iron sulfates (28, 31, 34, 35). Spectroscopy is consistent with ferric iron sulfates, indicating some oxidation (33, 36). The *Kukaklek* sample from a similarly light-toned outcrop (Fig. 3) in the western part of the explored area (Fig. 3) is somewhat coarser-grained and characterized as a sandstone (36). The numerous, cm-scale bright veins on this outcrop and some large grains in its abraded patch *Uganik Island* contain anhydrite (35, 36), suggesting more pervasive postdepositional fluid flow through this sediment. SHERLOC did not detect any Raman bands indicative of carbonaceous materials at any light-toned sulfate-rich outcrops, but it did measure strong doublet UV luminescence signals in the abraded patches. This luminescence was particularly strong in light-toned veins and grains, where SHERLOC Raman spectroscopy and PIXL X-ray fluorescence spectroscopy detected anhydrite. The strong UV-luminescence signal was initially attributed to one- or two-ring aromatic organic compounds (27), but the combined observations can be instead best interpreted as the inorganic doublet luminescence of Ce-bearing sulfate minerals (37).

The cross-stratified sandstones and pebble conglomerates that overlie the light-toned sulfate-rich deposits are interpreted as deltaic strata that formed by the transport of materials from the Jezero watershed forming multiple lobes of the sediment fan (31). Represented by the sandstone cores *Skyland* and *Swift Run*, these strata are the youngest components of the fan front stratigraphy (31). The rocks represented by *Skyland* and *Swift Run* contain detrital sand-sized grains of igneous and aqueously altered igneous minerals, i.e., materials transported from the Jezero watershed that may not be accessed by the rover in the future. A strong hydration signal and the detection of iron-magnesium carbonates around lithic clasts and in some composite grains (28, 33–35) suggest the precipitation of authigenic minerals from carbonate-bearing aqueous solutions. These rocks exhibit UV luminescence signals

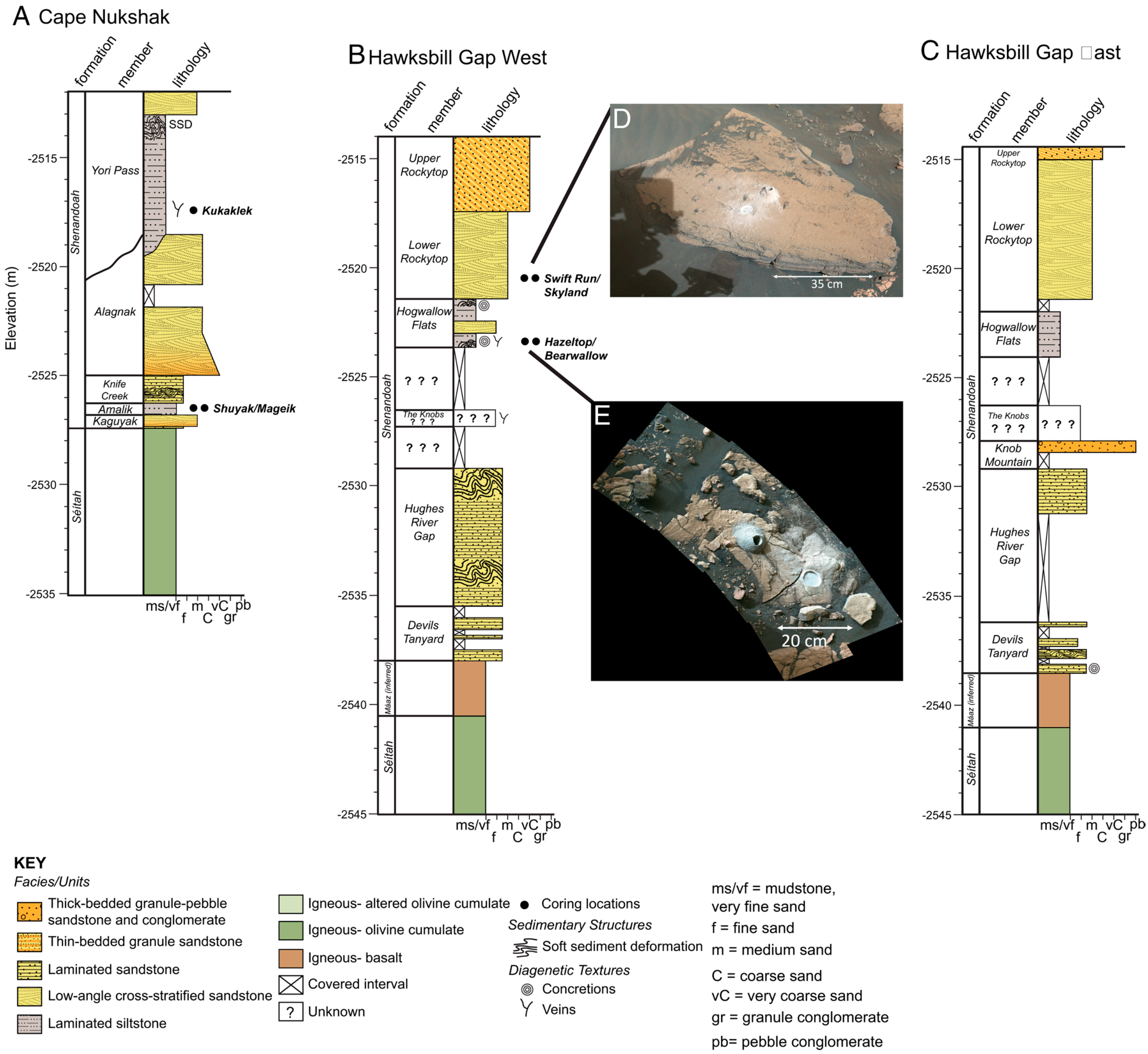

Fig. 3. Stratigraphic columns for the Shenandoah formation at (*A*) Cape Nukshak, (*B*) Hawksbill Gap West, and (*C*) Hawksbill Gap East. See ref. 31 for locations and other details. The *Inset* (*D*) shows the Mastcam-Z workspace image of the *Skinner Ridge* outcrop after sampling the *Swift Run* core. The tailings pile after sampling, as well as the 5 cm wide *Thornton Gap* abrasion patch, are visible. The inset (*E*) shows the tailings after sampling the *Hazeltop* core, and the 5 cm wide *Berry Hollow* abrasion patch.

primarily in areas that contained phosphate, as would be expected from Ce-containing phosphate minerals (37).

Potential Returned Sample Science. Upon the completion of the MSR Campaign, the suite of sedimentary rocks collected by Perseverance at the Jezero fan front could provide an entirely new window into martian habitability and the potential of the planet to initiate and sustain life more than 3.5 billion years ago (31). Due to their hydration and the presence of clay minerals and precipitated minerals such as Mg/Fe sulfates and the later anhydrite, the finest-grained rocks from the fan front have the highest value for astrobiology. These lacustrine mudstones/siltstones are conducive to the preservation of organic matter and biosignatures (e.g., refs. 36 and 38), particularly if they were not subject to extensive flow or percolation of oxidizing fluids during diagenesis (e.g., refs. 28, 38, and 39).

The Perseverance rover payload did not detect any conclusive signals of organic matter in the sampled sedimentary rocks (37). However, the rather low sensitivity of the SHERLOC instrument to carbonaceous material - relative to the instrumentation on Earth or on the Curiosity rover (e.g., refs. 37, 40, and 41) - emphasizes the need to search for organic materials in the returned samples of these rocks. These analyses can be coupled with petrographic, geochemical, and isotopic analyses of all returned sedimentary rock to search for textural and geochemical signals of life-related processes before and during the earliest stages of fan deposition (28, 36).

The lithic clasts and precipitated minerals in coarser-grained samples from the bottom and the top of the fan front stratigraphy can constrain both the timing and the duration of habitable conditions and past climate in Jezero crater, and more broadly, on Mars (28, 31). Moreover, geochronological analyses of carbonate cements in these rocks can be used to determine when the deltaic sediments became lithified (e.g., ref. 42), whereas isotopic analyses of mineral-bound water and carbonate and sulfate minerals across the sample suite can reconstruct the parallel histories of martian volatiles and paleoenvironment.

Fan Front Campaign Regolith Samples

Geological Context. The Perseverance rover has collected two samples from the inactive megaripple *Observation Mountain*: *Atmo Mountain,* which remains on the rover, and *Crosswind Lake,* which has been deposited in the Three Forks sample depot (Table 1). A megaripple was selected as a sampling location because megaripples have poor particle sorting (43, 44). A sample of a megaripple will therefore allow collection both of coarser, likely more locally derived materials, as well as fine-grained material that may come from more distant locations. The specific megaripple *Observation Mountain* was selected because it showed morphological features and grain size that indicate relative immobility (45), as well as a soil crust, widely observed at Jezero crater (46), that indicates the likely presence of substantial collected airfall dust. Because the Perseverance rover is able to sample to a depth of ~4 to 6 cm beneath the regolith surface, but the stratigraphy of the sample is not preserved, a scuff was generated to allow the analysis of the subsurface material (Fig. 4).

In situ analyses of the megaripple sediment indicate the presence of both mm-size lithic fragments and fine-grained material. The lithic fragments likely originate from at least two different source regions, and some of the lithic fragments lack a coherent diffraction pattern measured by PIXL, consistent with poorly ordered secondary phases (45). WATSON images and MEDA thermal inertia measurements of the fine-grained material collected from a depth of ~4 to 6 cm indicate grain sizes of ~125 µm and ~150 µm, respectively, denoting that its characteristics are similar to those of previously proposed global soils (45).

Potential Returned Sample Science. Analyses of the fine-grained material collected in the regolith sample would help to address the formation processes of the martian soil; a major unknown in Mars science. Formation of relatively uniform martian regolith in widely spaced locations on Mars that has been previously documented (e.g., refs. 47–50) may indicate either relatively uniform parent material across multiple widely spaced locations on Mars, or a truly globally mixed material; grain-by-grain examination of the regolith sample would help to address potential formation mechanisms. In addition, the presence of airfall dust in the sample would enable measurements of the composition, shape, and size distribution of dust grains to help better understand the radiative and microphysical effects of dust on past and present martian climate. Samples of dust would also allow an assessment of the risk to human health and equipment on future human missions (5). Also, although sampling disrupts the soil crust, the components of the soil crust likely have been collected within the volume of the sample tube, allowing the future assessment and characterization of these components.

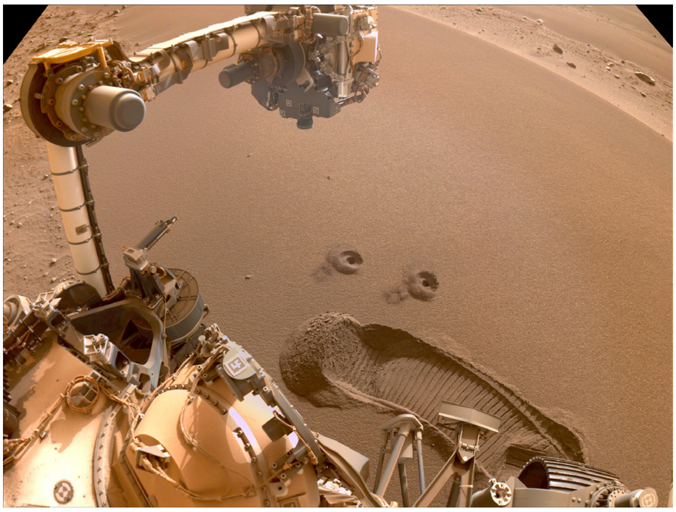

Fig. 4. Navcam image of the immobile megaripple *Observation Mountain* which contains the regolith sampling locations of *Atmo_Mountain* (*Left*) and *Crosswind_Lake* (*Right*). The rover performed a scuff to expose the subsurface material that likely makes up the majority of the sample, and analyses were performed of both the undisturbed surface, the wall of the wheel scuff, the wheel track, and the tailings pile from the scuff (see ref. 45 for details). For scale, the rover wheel is 33.6 cm wide.

As a sample containing a potentially high diversity of larger lithic fragments that themselves likely contain altered secondary phases (45), analysis of these fragments could preserve past potentially habitable, and possibly inhabited environments. As such, possible biosignatures could be present in these heavily altered materials. Three different patterns of fluorescence were detected by the SHERLOC instrument, patterns that are consistent with inorganic emissions from REEs or silica defects, with organic origins unable to be excluded (37, 45). Analysis of these materials in Earth's laboratories promises to better identify past potential biosignatures.

An additional aspect of the regolith sample is its potential for in-situ resource utilization (ISRU) technologies, to support the future sustained exploration of Mars; regolith has the potential to be used with additive manufacturing as a building material (51); as raw material to extract iron ore, silicates, and alumina; and as a substrate for biomining methods (52).

Upper Fan Campaign Samples

Geological Context. The Jezero upper fan, from which the cores *Melyn*, *Otis Peak*, and *Pilot Mountain* were acquired (Table 1), records the latest stages of aqueous activity in the crater and contains some of the coarsest-grained materials observed thus far. The upper fan is composed largely of two units identified from orbital data: the Delta truncated curvilinear (D-tcl) and Delta blocky (D-bl) units (11). Delta truncated strata are visible in orbital images as sets of 100 m arcing layers of alternating bright and dark layers. Rover images of the D-tcl Tenby formation, where *Melyn* was acquired, show that these layers correspond to resistant sandstones and recessive coarser grained rocks. Proximity science observations of the *Solva* abrasion patch paired with the *Melyn* sample indicate that the detrital grains are largely of mafic igneous origin, being composed of olivine, feldspar, possibly pyroxene, and minor Fe-, Cr-, and Ti-oxides and phosphate. The presence of hydrated sulfates, carbonate, and possibly also phyllosilicates and silica indicate that the materials experienced aqueous alteration (53).

These rocks clearly overly the fan front lithologies, although the contact is obscured. Delta blocky rocks, which sit unconformably over the older *Tenby* formation, consist of steep-sided lobes covered with boulders and poorly lithified materials. As observed in the *Otis Peak* formation, from which the *Otis Peak* and *Pilot Mountain* cores were acquired, these rocks are poorly lithified, granule and pebble conglomerates and sandstones covered by angular cobbles and boulders. Proximity science observations of the *Ouzel Falls* and *Gabletop Mountain* abrasion patches, which are paired with *Otis Peak* and *Pilot Mountain*, respectively, show that the clasts at this location are dominantly monomineralic and polymineralic and composed of altered olivine, carbonate, and polymineralic grains of feldspar and Cr spinels. These are cemented by silica, sulfate, and carbonate, again indicating aqueous alteration (54, 55).

Potential Returned Sample Science. The Upper Fan samples are of great value for returned sample science for at least two major reasons. First, they are collectively the youngest and stratigraphically highest samples acquired by the rover on the fan and could ultimately be the youngest samples acquired by the rover during the full mission. As such, geochronological analyses could put an upper bound on the timing of fluvial activity in the crater and, when combined with ages from crater floor and fan front samples, constrain the duration of fluvial activity. Furthermore, given current age constraints on the fan (31), these samples are from lithologies thought to be Hesperian in age. Given that there are no known Hesperian martian meteorites (Udry et al. (56)), the Upper Fan samples will fill a critical gap in the rock record available for laboratory analyses from this crucial juncture of major climate change in martian history.

Second, the Upper Fan samples contain the coarsest detrital grains yet sampled by the rover. Some of these clastic materials are almost certainly derived from the Nili Planum region outside Jezero that serves as the watershed for Jezero lake. As such, these detrital materials offer two unique opportunities for returned sample science investigations. They provide samples from distal regions up to 200 km from the western crater rim that will likely never be sampled in situ by the rover; these also include some of the oldest known rocks from Mars (e.g., ref. 57) and so will provide invaluable records of early planetary processes, e.g., magmatism, aqueous activity, climate, and the evolution of the martian dynamo. Many of the rocks are also thought to be from deeper parts of the crust and possibly even the mantle. Therefore, these samples may provide records of planetary differentiation and sample a subsurface potentially habitable environment distinct from the surface waters of Jezero lake. Laboratory investigations of these samples will enable the study of a source-to-sink sedimentary system on Mars that will inform how aqueous processes and habitability evolved through time, both within the catchment and the fan. Crystallization ages of detrital igneous silicate clasts will provide upper bounds on the timing of fan deposition and therefore the timing of lake Jezero. Furthermore, the potential exists for, the coarse grains in these samples to enable a conglomerate test that can constrain the ages of paleomagnetic records in the samples. Records that predate deposition will tend to be expressed heterogeneously between different clasts, whereas records acquired secondarily after deposition will tend to be expressed homogenously across clasts and within the matrix.

Margin Campaign Samples

Geological Context. The Margin unit—situated at the interior of, and adjacent to, the western crater rim—is primarily of interest for the strong carbonate signal recognized in orbital reflectance spectroscopy data (11, 58), in addition to the potential presence of hydrated silica (59). Stratigraphically, the unit lies beneath the previously explored curvilinear and blocky units of the fan top and is therefore older than those units (60). The position of the Margin unit relative to other fan deposits and the crater floor units is unknown (11); it is possible this is one of the oldest units explored so far. Based on its position near the crater rim and the strong carbonate detections, the Margin unit has been proposed to be a shoreline deposit with possible lacustrine carbonates (58). Alternative hypotheses include pyroclastic, extrusive igneous, fluviolacustrine, and aeolian deposits, or a combination of several mechanisms (60–64).

The planning of the Margin campaign took place during the summer of 2023, and continues at the time of writing. Between 3 and 5 samples are baselined to be collected, and three have been so far successfully obtained (Table 1): the *Pelican Point* core at the Hans Amundsen Memorial Workspace in the Mandu Wall region, the *Lefroy Bay* core at Lake Newell in the Turquoise Bay region, and the *Comet Geyser* core at the *Bunsen Peak* outcrop. Data from the *Castle Geyser* sample abrasion patch associated with the *Comet Geyser* sample have yet to be processed and interpreted at the time of writing. *Pelican Point* and *Lefroy Bay* were collected from the eastern part of the Margin (Fig. 1), corresponding to near the regolith-covered contact to Lobe H of the western fan as mapped by (65). The location of the *Lefroy Bay* sample (*Lake Newell*) is slightly higher in elevation and located in a more carbonate-rich area as indicated by orbital data (58). The outcrops at both locations exhibit a similar appearance: low-lying, granular, fractured, and minimally layered slabs of in-place bedrock. Plane-parallel laminations were observed near the sampling outcrops, some at low dipping angles (63); in contrast, more resistant, massive rocks are present looking west into the Margin unit.

Proximity observations of the abrasions *Amherst Point* and *Bills Bay* (corresponding to *Pelican Point* and *Lefroy Bay*, respectively) indicate clastic rocks of likely sedimentary origin, classified as moderately to poorly sorted medium- to coarse-grained sandstones. Both abrasions contain similar mineral assemblages, as indicated by PIXL, SCAM, and SHERLOC data, primarily containing olivine, pyroxene, and altered silicates such as serpentine, Mg–Fe carbonates, and a high-silica phase, likely as a pore-filling cement (66–68). The bulk composition is consistent with that of an altered basalt and is in family with the fan top samples; minor phases include Mg-sulfates, oxides, feldspar, and chlorides (67). In *Amherst Point* the carbonate mostly appears as coatings while in *Bills Bay* carbonate is also present as clasts; carbonate is also more abundant in *Bills Bay.* SHERLOC data indicate that some of the silica in *Bills Bay* is hydrated silica. SHERLOC data also indicate that some of the carbonates in *Amherst Point* are hydrated; this represents the first time during the mission that such carbonates have been detected. The hydrated carbonates appear in bright patches together with hydrated sulfates. The very low fluorescence signal and absence of Raman signals indicate that any organic materials present are in the sample in low abundance (<0.1 wt%) (37).

Potential Returned Sample Science. Margin samples are of high interest for constraining the timing of lake Jezero through geochronology of clasts and cements in the cores. The cements may also constrain aqueous geochemistry (pH, Eh, salinity, etc.) and potential fluid sources. Together with the fan samples, these materials would be used to understand sources to sinks in sedimentary systems on Mars as some clastic material is likely detrital material sourced from outside Jezero crater. Chemical characterization of alteration phases would provide insights into sediment diagenesis. As expected from orbital data, rocks in the Margin are rich in carbonate; carbonate chemistry would constrain the climate of Mars at the time of deposition and/or diagenesis, may allow inferences about the aqueous chemistry and paleoenvironmental conditions of lake Jezero to be made, and would contribute to reconstructing past martian climate.

If the interpretation of the Margin as a possible shoreline/lacustrine deposit is correct, the presence of minerals formed by water would indicate that the Margin unit was once a habitable environment. Lakeshore environments are known to be habitable in similar settings on Earth and are commonly colonized by microbial communities, for example, microbial mat ecosystems. Lacustrine shoreline environments on Earth are frequently characterized by rapid mineral precipitation, which presents ideal conditions for preserving biosignatures (e.g., refs. 38 and 58). The carbonate and silica grains/precipitates identified in the Margin sequences may therefore have trapped biosignatures and organic molecules in a similar manner (e.g., ref. 39). Furthermore, parts of the observed carbonate and silica in the Margin unit abrasion patches appear microcrystalline—a characteristic that promotes biosignature preservation (e.g., ref. 39). Combined with the fact that these samples might be one of the oldest samples collected so far, they are of high astrobiological interest. Biosignatures preserved in such sequences on Earth typically include diverse biological microfabrics and microstructures; assessing the morphological and geochemical signatures of life associated with such materials is dependent upon high-resolution laboratory characterization.

Anticipated Samples from the Jezero Crater Rim and Beyond

The region beyond the areas previously and currently explored by the Perseverance rover mission comprises diverse rock units exposed within the Jezero crater rim; these rock units are almost certainly distinct and thus have not yet been investigated or sampled. Within the overall stratigraphy of Jezero crater, the rocks of the crater rim (and beyond, in Nili Planum) represent materials from Mars' most ancient crust (69, 70) that may be significantly older than those sampled in Jezero crater. These rocks potentially preserve a variety of geologic processes, potential ancient habitable environments, and regional stratigraphy that may link to the Jezero crater floor and to units beyond the crater rim.

The uplifted diverse Noachian Basement units were deposited prior to the ~3.9 to 4.1 Ga Isidis impact basin (57, 69, 70) and the Jezero crater forming impact; exploration of these rocks will be the first opportunity to investigate the oldest and deepest rocks on Mars (57, 69, 70). Within the crater rim, there are three components of the Noachian basement that the rover is likely to encounter that are high-priority exploration and sample targets: 1) A layered/stratified unit. This unit is composed of decameter-thick layers likely containing Fe/Mg smectite, based on Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) data (57). Smectite clays result from water/rock interaction and have high biosignature preservation potential (e.g., ref. 38). Abundant clays are present in the oldest rocks on Mars, suggestive of more intense alteration than that experienced by younger units in the region (57). Sampling these rocks and analyzing them on Earth would offer the opportunity to constrain processes involved in the

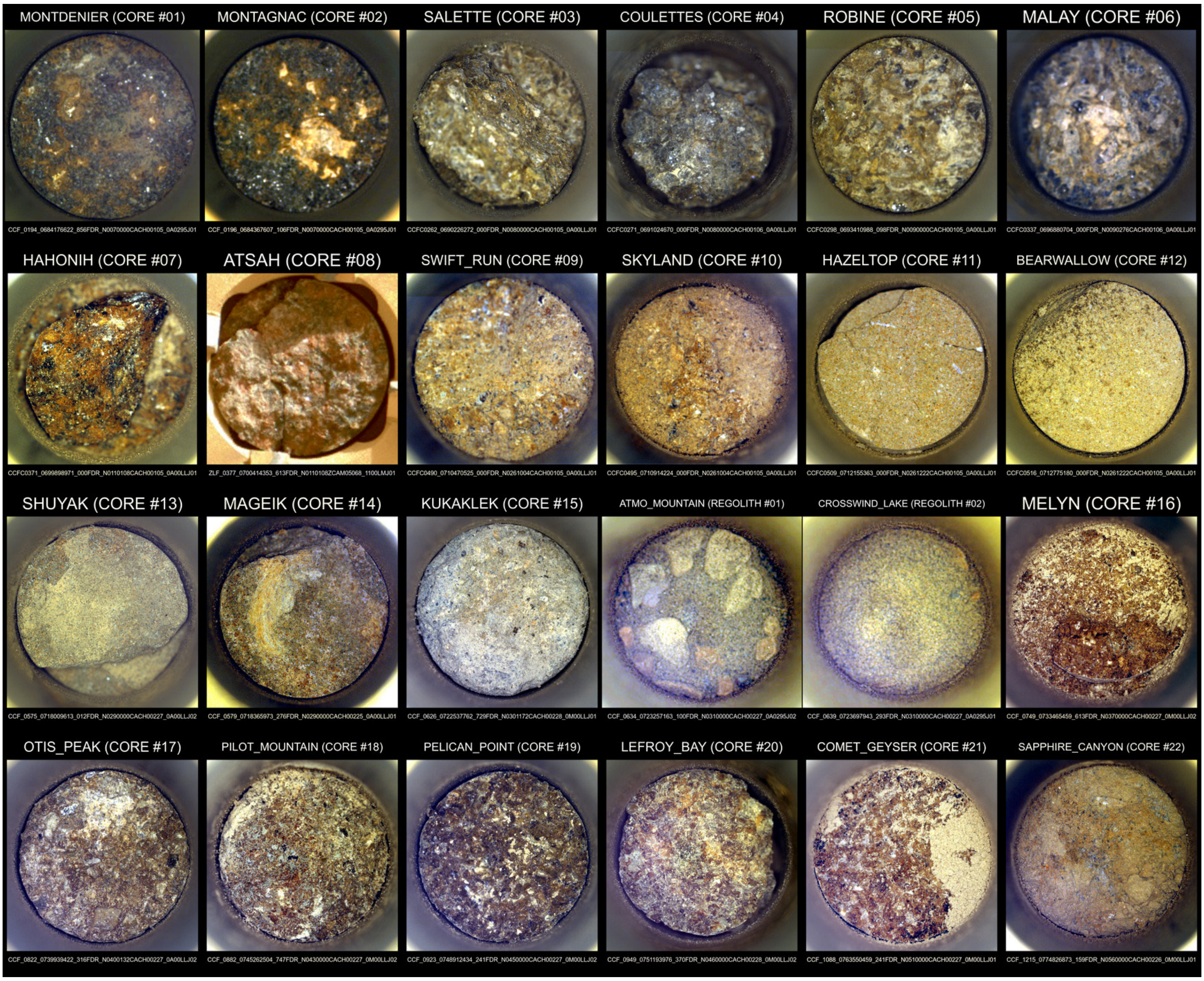

Fig. 5. Images of core samples collected to date (cf., Table 1). All images from Cachecam with the exception of Atsah (core #8); a Mastcam-Z image is provided instead. Core diameter in each case is 13 mm. Witness tubes are not shown.

formation of the earliest martian crust as well as weathering and alteration processes linked to early climate and associated ancient paleoenvironments and their habitability. 2) The blue-fractured unit. This unit is a distinct within the Noachian basement and possesses a blue color in High Resolution Imaging Experiment (HiRISE) data and a unique low-Ca pyroxene (LCP) signature (57). This unit has little to no Fe/Mg-smectite in CRISM data, indicative of limited alteration (57). The dominant presence of reduced iron (Fe^{2+}) is interpreted as indicative of igneous materials, predating or formed during the Isidis impact (57, 70). A sample of this unit would retain chemical signatures from early crustal evolution following accretion and, if determined to represent Isidis impact melt, could provide a unique constraint on the timing of the Isidis impact and thus on the martian geologic timescale. 3) Megabreccia. The megabreccia are a remarkable feature of Nili Planum near Jezero, composed of blocks up to 100s of m in size with a wide variety of albedos, textures, and lithologies. These blocks likely include some of the oldest rocks on Mars (57). Sampling of megabreccia could represent a wide diversity of pre-Isidis impact crustal materials, and samples would enable investigation of ancient basement rocks. Analysis on Earth would reveal insights into the earliest planetary evolution processes including crust formation, and the strength and timing of the dynamo and whether its evolution drove the loss of an early atmosphere (71). In many cases, the megabreccia contain Fe/Mg-smectite-bearing, often stratified materials linked to the same questions of biosignatures, climate, and habitability as the layered/stratified unit (57). In addition to these three "mappable" units, a kaolinite-bearing block has been identified in the rim that could represent the result of extensive weathering and alteration, such as observed in widespread Noachian weathering profiles (72, 73) its investigation could provide further insight into the earliest climate evolution and habitable environments.

Two other regional units present in the Jezero crater rim are high-priority targets: the ~3.8 Ga olivine-carbonate and mafic capping units. Investigation and sampling of these rocks would test connections to the broader geology of Nili Planum, Nili Fossae, and Syrtis Major and to similar units on the crater floor. Understanding these relationships is key to determining the emplacement mechanisms and timing of these units. Importantly, these units postdate, and therefore were likely unaffected by, the Jezero impact (74, 75). Sampling and geochronological analysis on Earth of samples of these regionally widespread units would help to calibrate ages derived from crater counting, i.e., the chronology of Mars. The presence of carbonate in association with olivine indicated from orbital observations (e.g., ref. 58) is suggestive of water/rock interaction and may provide information about the loss of early martian surface water to weathering interactions with the crust (76). On Earth actively reacting olivine-rich rocks provide both nutrients and habitats for subsurface biospheres (e.g., ref. 77).

High-priority opportunistic targets are more difficult to identify and locate from orbit but are key geologic features to investigate within the crater rim. These include hydrothermal features and impact-generated melt (78). Hydrothermal precipitates and/or mineralized veins would provide insights into hydrothermal activity and alteration, possibly linked to crater formation, as well as deep groundwater circulation that could have created long-lived habitable environments. Such rocks may have high astrobiological and biosignature potential. Impact melt or other impactites would provide the opportunity to determine the age of the Jezero impact, further constraining the chronology of Mars.

Concluding Remarks

The samples on board Perseverance represent a diverse suite of geological and atmospheric materials (Fig. 5) that address the majority of community-defined objectives for MSR (Fig. 6), including characterization of geological settings, potential habitability, constraints on the chronology of Mars, and planetary-scale geology including how and why the climate and interior of the planet have changed through time (5). Although the samples deposited in the Three Forks depot would address most of these objectives (79), the Three Forks depot does not include samples from the Upper Fan or Margin Campaigns. The samples onboard

iMOST Objectives	Samples 3, 4, 9, 10: Basaltic igneous	Samples 5, 6, 7, 8: Cumulate igneous	Samples 11, 12: Medium sedimentary	Samples 14, 15, 16, 17, 19: Fine sedimentary	Samples 20, 21: Regolith	Samples 22, 23, 24: Medium to coarse sed.	Samples 25, 26, 27: Clastic sed. ? (+ carbonates, silica)
	Crater Floor		Delta Front			Upper Fan	Margin
1. Geol. Environ. (Jezero)							
1.1 Sedimentary system	○	○	●	●	◗	●	●
1.2 Hydrothermal	◗	◗	○	○	○	○	◗
1.3 Deep groundwater	◗	◗	○	○	○	○	◗
1.4 Subaerial	◗	◗	●	●	◗	●	●
1.5 Igneous terrain	●	●	◗	○	●	◗	◗
2. Life							
2.1 Carbon/organic chem.	◗	◗	◗	●	◗	◗	◗
2.2 Ancient hab./biosig.	◗	◗	●	●	●	●	●
2.3 Modern hab./biosig	●	●	●	●	●	●	●
3. Geochronology	●	●	●	○	◗	●	●
4. Volatiles	◗	◗	◗	◗	◗	◗	◗
5. Planetary Scale Geology	◗	◗	◗	◗	○	◗	◗
6. Environmental Hazards	◗	◗	◗	◗	●	◗	◗
7. ISRU	○	○	◗	◗	◗	◗	◗

● =Likely to fully address objective; ◗ =Likely to partly address objective; ○ =Unlikely to address objective

Fig. 6. Traceability matrix between the samples collected by Perseverance and the community objectives for MSR ["iMOST Objectives" (5)]. ISRU = in situ resource utilization. Sample numbers correspond to the numbering provided in Table 1.

Perseverance include both sedimentary and igneous rocks; sedimentary rocks include mudstone, sandstone, and conglomerate representative of lacustrine, deltaic, and fluvial environments, whereas igneous samples represent extrusive and intrusive settings. Multiple potentially habitable environments and microenvironments are preserved across the sample suite. The fluvial environment and coarse-grained nature of some of the samples mean that lithologies from outside Jezero are also included in the suite.

The crater rim potentially records Noachian geology not previously explored by any Mars mission; obtaining further samples from this area would significantly expand the scientific value of the current sample cache. Exploration and sampling of the crater rim would access 1) a diversity of ≥4 Ga martian crustal materials that preserve records of ancient climate, habitability, magnetic dynamo, and crustal formation processes; 2) ancient uplifted potentially habitable subsurface environments that could preserve biosignatures; and 3) materials from crater retaining surfaces and/or impactites that could be used to constrain the martian timescale. Samples of rim materials would enhance the overall scientific value of MSR, and justify NASA and ESA investment in this effort. Analysis of these samples in terrestrial laboratories—in the immediate years after return and in the decades to follow—would provide a level of evidence approaching definitive, beyond what is possible with in situ science at Mars. Such analyses would enable the investigation of Decadal-level scientific questions outlined by the Mars community (5, 80–82).

Materials and Methods: Description of the Mars 2020 Perseverance Rover Payload

The Mastcam-Z (Mast Camera Zoom) stereo color imaging system (83) acquires high-resolution, 360-degree panoramic landscape images that document the geomorphology, texture, structure, and stratigraphy of the sampling locations and surrounding regions. Mastcam-Z also acquires color images of the sample core tops prior to sample processing. The mast-mounted SuperCam instrument (84) acquires data for laser-induced breakdown spectroscopy (LIBS), remote time-resolved Raman and luminescence spectroscopy, visible/infrared reflectance spectroscopy, and high-resolution color context imaging. The arm-mounted PIXL (Planetary Instrument for X-ray Lithochemistry) instrument (85) acquires high-resolution X-ray fluorescence spectra with 120 μm spatial resolution to provide chemical maps of major, minor, and trace element chemistry of the sampling locations. The SHERLOC (Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals) instrument (86), also mounted on the arm, acquires deep-UV fluorescence and Raman spectra. The spectra from both of the arm-mounted instruments are correlated to high-resolution context camera images from each instrument. The SHERLOC instrument also acquires high-resolution, color macroscopic images of the sampling area using the WATSON (Wide Angle Topographic Sensor for Operations and eNgineering) camera. Image data are also acquired by a suite of engineering cameras (87): the Navcam and Hazcam cameras provide comprehensive documentation of the sampling area topography, and the Cachecam camera acquires high-resolution color images of the sample core tips immediately prior to tube sealing. After the samples are documented, they are processed by and ingested into the Sampling and Caching System (SCS), described in ref. 8. Additional context data are provided by a ground penetrating radar instrument, RIMFAX (88), and a weather station, MEDA (89).

Data, Materials, and Software Availability. All study data are included in the main text.

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