Evolution of the Mars 2020 Perseverance Rover's Strategic Planning Process

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Abstract—**The Perseverance rover has completed three scientific campaigns in Jezero crater, Mars, encompassing the following regions: 1) Crater Floor, 2) Fan Front, and 3) Upper Fan. During that time, the mission has collected 21 samples, traversed 21 km of distance, and deposited 10 samples at the Three Forks location near the base of the Fan Front. Perseverance's progress has been enabled by efficiencies in the Mars 2020 operational processes at both the strategic and tactical levels. Strategic planning is an especially important process given Perseverance's role in the Mars Sample Return campaign as the potential sample delivery mechanism to the Sample Return Lander in the future. In this work, we discuss the evolution of strategic planning on the Perseverance mission, and compare predicted, strategically-developed campaign plans with the actual executed mission. The strategic campaign planning process establishes a campaign's science objectives and provides an estimate of its duration and sample collection count in advance of its execution. Sols are primarily allocated for sampling, driving, science, and engineering activities, with a proportion of sols held as margin to account for unexpected events or discoveries. Perseverance's anticipated exploration of a campaign area is captured as a baseline sol path or campaign calendar that considers: orbiter schedules, solar conjunction, and Earth schedules such as holidays. This campaign plan is fed into the Campaign Implementation and Tactical processes, which produce activity plans that are uplinked as a complete sequence bundle at the end of each planning day. As tactical plans execute, a sol-by-sol record of the executed campaign is documented, enabling comparison to the initial campaign calendar. The above process has been used to plan each of Perseverance's first three science campaigns. Following the completion of each campaign, assumptions and lessons learned from that campaign are fed forward into the planning of the subsequent campaign, such as updates to proportion of margin sols, updated mobility estimates, and new operational efficiencies and rover capabilities. In general, the proportion of campaign-advancing sols has increased with each campaign. The Mars 2020 mission has now accumulated a robust record over 900 sols of the strategically planned versus executed activities of the rover. Continued feedback from the strategic planning process will continue to improve the efficacy of predictive mission planning on Mars 2020, increasing our ability to allocate resources more accurately for future campaigns and ensuring that Perseverance fulfills the expectations of the evolving Mars Sample Return campaign. The data and lessons from Mars 2020's strategic processes will also provide a template for strategic mission planning for future planetary missions.**

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1. INTRODUCTION

Since landing on February 18, 2021, the Mars 2020 Perseverance rover has been exploring an ancient lake environment at Jezero crater, Mars and caching samples for potential return to Earth by a future sample return mission. As of writing, Perseverance has explored the majority of the geologic units within the crater throughout three scientific campaigns in three geographic regions **(Figure 1; Table 1)**: 1) the Crater Floor, 2) the Fan Front, and 3) the Upper Fan. After landing, the Perseverance team spent the first 99 sols performing commissioning activities and supporting the Ingenuity flight demonstration [1,2], while also planning the exploration strategy for the first science campaign on the Crater Floor. Perseverance explored the Crater Floor from sols 99-378 and then performed a rapid traverse campaign [3,4] towards the Fan Front from sols 379-410. Exploration of the Fan Front during a second science campaign occurred during sols 411-641, after which Perseverance deposited 10 sample tubes as a backup sample depot at the Three Forks location near the base of the fan front between sols 642-693. A brief period of Fan Front campaign activities resumed between sols 694-707, after which Perseverance executed its third science campaign on the Upper Fan between sols 708-910. Perseverance began its fourth science campaign in the Margin unit on sol 911 and is currently ongoing as of writing.

Throughout 910 martian sols and 935 Earth days spanning its first three science campaigns, Perseverance has collected 21

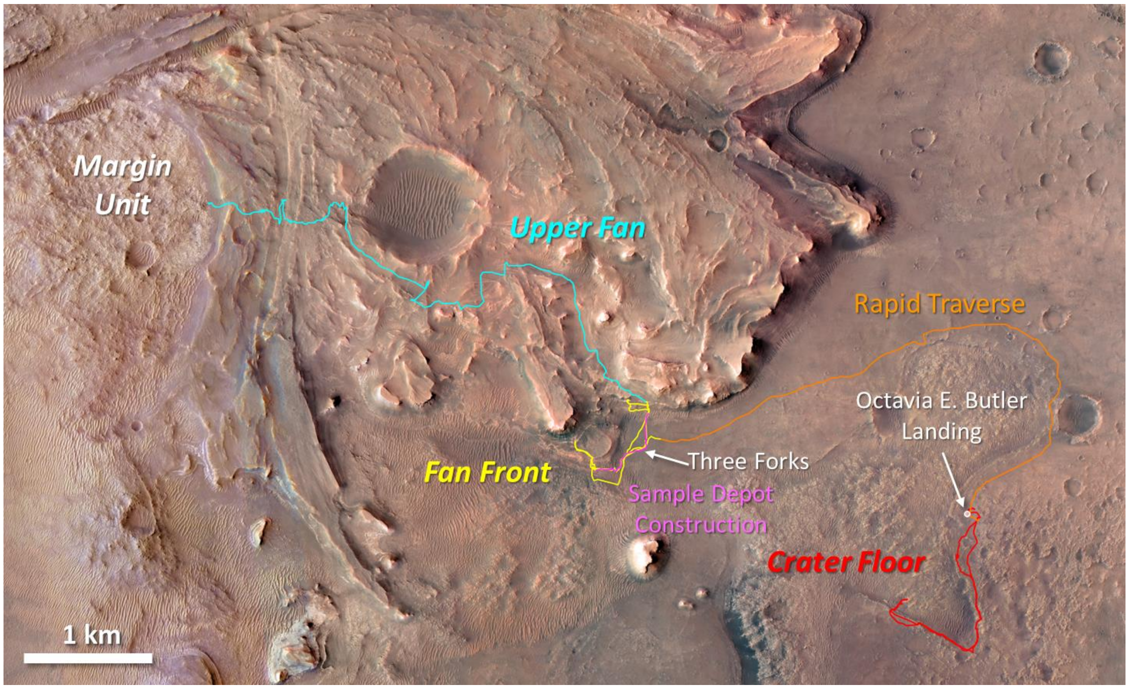

Figure 1. Overview of Jezero crater, with Perseverance's actual traverse through three scientific campaign areas covering the Crater Floor, Fan Front, and the Upper Fan. Currently, Perseverance is exploring the Margin unit in its fourth scientific campaign.

Sols *(Dates)*	Event	Drive Distance	Samples Collected	Unique Lithologies Collected
1-99 *(Feb 18 – Jun 3, 2021)*	Commissioning and Ingenuity flight demonstration	387 meters	0	0
100-378 *(Jun 4, 2021 – Mar 13, 2022)*	**Crater Floor campaign**	4541 meters	9	5
379-410 *(Mar 14 – Apr 15, 2022)*	Rapid Traverse to Fan Front	5063 meters	0	0
411-641; 694-707 *(Apr 16 – Dec 8, 2022; Feb 1 – Feb 14, 2023)*	**Fan Front campaign**	3800 meters	9	5
642-693 *(Dec 9, 202 – Jan 31, 2023)*	Sample Depot Construction	669 meters	0 (10 tubes deposited)	0 (8 unique lithologies, 1 atmospheric sample, 1 witness tube deposited)
708-910 *(Feb 15 – Sep 11, 2023)*	**Upper Fan campaign**	6822 meters	3	3
911+ *(Sep 12, 2023)*	**Margin campaign**	n/a	n/a	n/a

Table 1. Summary of Perseverance's major campaigns and events and the associated drive distance and samples acquired.

samples (representing 13 unique rock or regolith lithologies), traversed more than 21 km of distance, and deposited 10 sample tubes for potential retrieval by a future sample return mission. Perseverance's rapid progress compared to its predecessors (e.g., the Mars Science Laboratory Curiosity rover) was enabled not only by technological advances [2,4,5] but also by efficiencies in the Mars 2020 operational processes at both the strategic and tactical levels [6], which have been continually refined and improved over the course of the mission.

Strategic planning, which aims to establish the mission's objectives and schedule over the timescale of Perseverance's entire mission, is an especially important process given Perseverance's role in the Mars Sample Return campaign as the primary sample delivery mechanism to the Sample Retrieval Lander. In this work, we discuss the evolution of strategic planning on the Perseverance mission, and compare predicted, strategically developed campaign plans with the actual executed mission. This iterative feedback, collected over 910 sols, will continue to improve the efficacy of predictive mission planning on Mars 2020, and will ensure that Perseverance fulfills the expectations of the evolving Mars Sample Return Campaign. This analysis will also contribute to the accuracy of strategic planning for future planetary missions.

2. PERSEVERANCE'S MISSION OPERATIONS STRUCTURE

The Mars 2020 mission's operations structure consists of four parallel processes that are interdependent and feed into one another as described in [6,7]. The Strategic and Campaign Planning processes are the broadest in scope and aim to establish the overarching objectives and priorities that guide the team's day-to-day activities throughout the mission.

The Strategic Process

The Strategic process, led by project management and project science leadership, determined the regions in Jezero that Perseverance would focus on exploring through science campaigns and allocated approximate time durations to conduct those campaigns **(Table 2)**. Each campaign was also allocated a notional number of samples to collect, out of the 38 sample tubes (to be filled with rock/regolith samples) and the 5 witness tubes (intended as a "control" tubes to document any contaminants the sample tubes could have been exposed to on Mars, Earth, or in transit to Earth) carried on board Perseverance. As a result of a multi-year landing site election process [8], it was determined that Perseverance would land in Jezero crater and explore the ancient lake environment preserved within, but that it would also later traverse outside of Jezero crater, investigating the crater rim and the Nili Planum terrains outside of Jezero which have been hypothesized to represent ancient subsurface habitable environments. This would enable the mission to explore and collect a sample cache that captured high priority rock lithologies representing the diversity of the environments preserved in both Jezero crater and Nili Planum [9,10].

It was thus determined by project leadership that the first three Earth years, or 1.5 Mars years (the qualified lifetime of the rover), of the mission would focus on investigating Jezero's interior units, with approximately one Earth year allocated to exploring each of Jezero's major geographic areas of interest: the Crater Floor, the Fan (later separated into

	Crater Floor		Fan Front		Upper Fan	
	Planned	Actual	Planned	Actual	Planned	Actual
Start Sol:	99		411		708	
End Sol:	346	378	652	707	944	910
Length (Sols):	248	280	242	246*	237	203
Unconstrained Sols (% of total sols):	197 (79%)	207 (74%)	150 (62%)	150 (61%)	138 (58%)	117 (58%)
Constrained Sols (% of total sols):	51 (21%)	50 (18%)	92 (38%)	96 (39%)	99 (42%)	86 (42%)
Drive Sols:	72	62	38	48	41	35
Sampling Sols (# Sample Tubes):	44 (8)	57 (9)	31 (6)	60 (9)	32 (4)	46 (3)
Science Sols:	19	14	31	12	24	17
Commissioning/Flight Software Sols:	16	14	5	4	5	3
Other Eng Sols:	0	3	10	4	5	1
Engineering Margin/Fault Sols (% of Useful Sols	23 (15%)	61 (41%)	35 (30%)	52 (41%)	35 (32%)	47 (46%)
Conjunction Sols:	23	19	0	0	0	0
Useful Sols (% of total sols):	151 (61%)	150 (54%)	118 (49%)	128 (52%)	107 (45%)	102 (50%)
Burn Rate:	156%	115%	95%	108%	82%	101%
				*excludes 51 sols associated with Sample Depot Construction		

Table 2. Summary of initial sol allocations compared to the actual executed sols for the Crater Floor, Fan Front, and Upper Fan campaigns.

the Fan Front and Upper Fan), and the Margin unit [9]. During this time, Perseverance would collect samples, a subset of which would be placed in a first depot. The remaining sample collection would eventually contain samples from both Jezero and Nili Planum and could be the primary intended target for a future sample return mission to retrieve and send back to Earth. The first, smaller depot would contain samples only from inside Jezero and would be deposited within Jezero crater before the end of Perseverance's prime mission to serve as a contingency cache should Perseverance become unable to deliver or deposit the other samples. This caching strategy resulted in the implementation of a paired sampling strategy [11] wherein each unique sample collected before the first sample depot construction would be paired with a companion sample from the same location. One sample of each pair would be deposited in the first depot within Jezero crater, and the other sample would be carried within Perseverance for future caching or transfer to the Mars Sample Return Sample Retrieval Lander. Maintaining this schedule necessitated a robust Strategic and Campaign Planning process, and required an adherence to the strategic sol path as much as possible in the Campaign Implementation and Tactical processes.

The Campaign Planning Process

The Campaign Planning process takes the initial duration and sample estimates from the Strategic process and uses orbiter datasets and analyses to produce a campaign plan, which identifies: 1) the scientifically important locations to explore, 2) the strategic drive path between these locations, 3) a notional sampling plan that includes the number, rock type, and location of samples, 4) time needed for scientific activities not associated with sampling, and 5) potential decision points that may influence the campaign as on-the-ground data is acquired.

The campaign plan is then captured as a baseline sol path that accounts for: orbiter schedules, solar conjunction (a period of time where Mars and Earth are on opposite sides of the Sun and cannot communicate), and Earth schedules such as holidays on which the mission does not uplink a plan. In order to assemble this baseline sol path, each campaign sol is notionally allocated according to the scheme described below and in **Table 3**.

Sol Allocations

Due to the differences between the length of an Earth day and a Mars sol (with a martian sol being ~40 minutes longer than an Earth day), campaign sols are categorized at a high level as either unconstrained sols and constrained sols. A sol is unconstrained if it receives sufficient data from the receding sol to ensure the safe execution of any type of activity that can advance the sol path (e.g., driving, sampling). **Constrained Sols** are those that lack sufficient data return from the preceding sol to plan certain campaign-advancing activities and are therefore not as productive as an unconstrained sol. For example, early in the mission, it was not possible to drive on a constrained sol because the team would have lacked knowledge of rover position from the previous sol. For purposes of creating a baseline sol path during campaign planning, constrained sols are assumed to be not campaign-advancing.

Campaign-advancing sols, referenced in **Tables 2 and 3** as **Useful Sols**, are divided amongst sampling, drive, science, and engineering sols. **Sampling Sols** include a choreographed sequence of activities including abrasion, abraded proximity science, and sampling, and are allocated as 11-12 sols per sample pair (relevant during the prime mission prior to the first depot), or 8-10 sols per single sample (relevant after the first sample depot construction) [11]. **Drive Sols** are dedicated to sols containing a drive of some assumed average distance, although some time for science activities is usually also possible. Science activities, which are significantly less power-intensive than the drive, can generally be planned on drive sols at no additional cost to the sol path. **Science Sols** are those on which science activities use most of the available rover resources, thus precluding driving or sampling activities due to time or power limitations. Science sols are allocated when an entire sol is used for remote sensing observations or proximity science (using the instruments on the robotic arm). **Engineering Sols** are allocated to sols where engineering activities largely preclude any of the above sol types. For example, the Crater Floor campaign allocated engineering sols to execute commissioning activities that were not completed during the first 99 sols of the mission. Engineering sols are also used when transitioning the rover's flight software periodically during the mission, or when sol path progress is halted due to upgrading ground software tools or other Earth-based testing.

	Total Sols						
Sol Allocations	Constrained Sols	Engineering Margin*	DSN Margin**	Sampling***	Drive	Science	Engineering
Metrics	Not useful sols			Useful Sols			
* 15-30% Engineering Margin depending on campaign							
** 1 DSN Margin sol/month							
*** 8-11 sols per sample/sample pair							

Table 3. Summary of how sols are allocated during the Campaign Planning process and when tracking campaign progress during campaign execution on Mars.

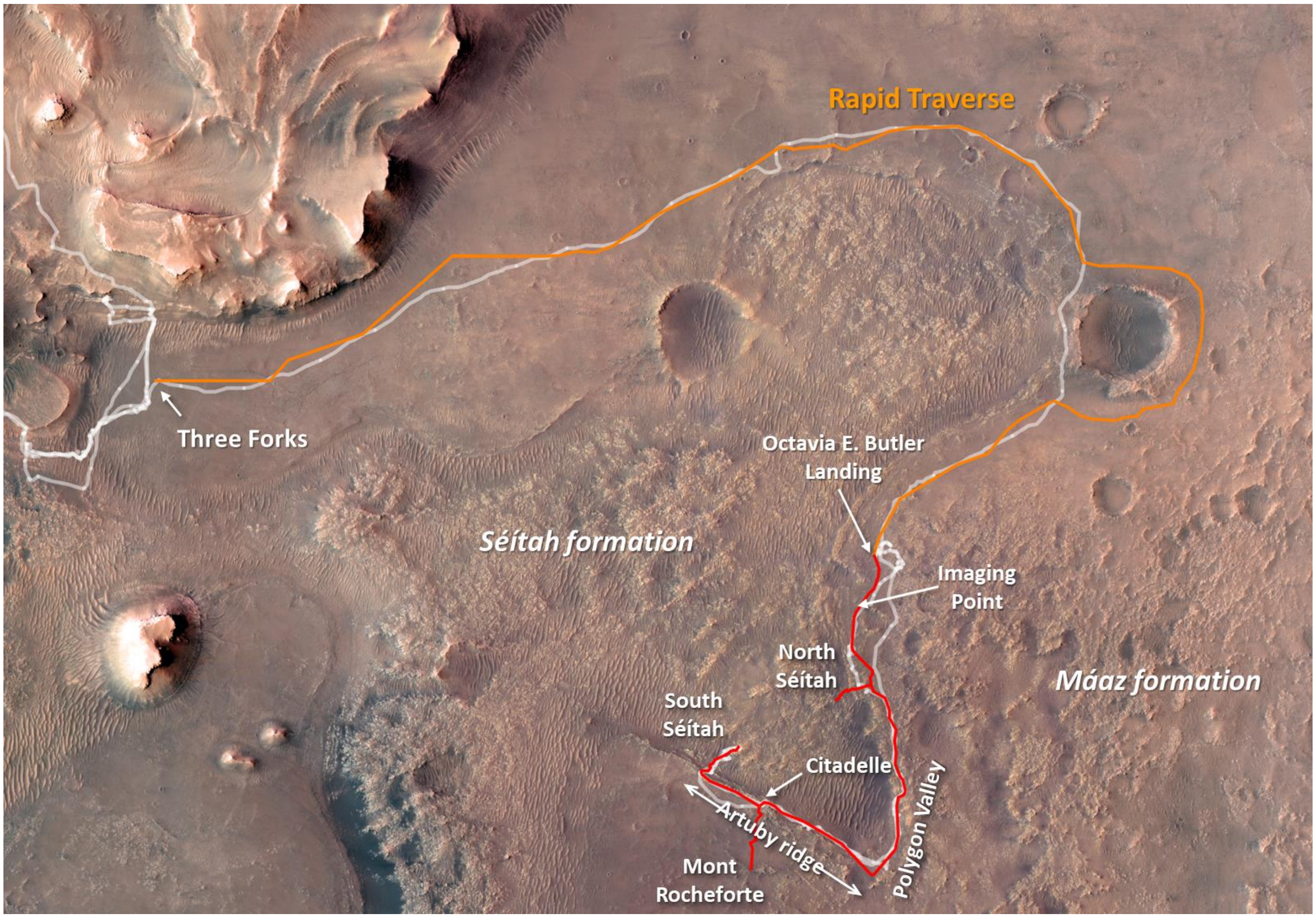

Figure 2. Comparison of the planned traverse for the Crater Floor campaign (red), the planned traverse for the rapid traverse drive campaign to Three Forks (orange), and Perseverance's actual drive path (white). Landmarks referenced in the text and in Table 4 are labeled.

Of the Useful Sols, a proportion (ranging from ~15-30% in the first three campaigns) are applied as **Engineering Margin Sols** in case of unexpected events such as faults. An additional sol per month is allocated to **DSN** (Deep Space Network) **Margin Sols**, to be used when uplink opportunities are lost due to DSN maintenance or another mission's launch. A baseline **Burn Rate** is also calculated as the ratio of sols that progress the sol path (i.e. Useful Sols) to those that do not (e.g., margin sols). As the campaign executes on Mars, the present-day Burn Rate is compared to the baseline Burn Rate value to assess if the campaign is ahead of schedule (i.e. the current Burn Rate is greater than the baselined Burn Rate) or behind schedule. During campaign execution, sols in which activities do not execute as expected and impede campaign progress (e.g., if a drive cuts off much shorter than expected, or critical instruments are marked sick, or the DSN does not transmit the plan to Mars) are categorized as **Fault Sols**. The **Fault Rate** is also monitored relative to the applied Engineering Margin to ensure that we are on track. The baseline campaigns established for each science campaign, as well as how planning parameters evolved (such as the percentage of engineering margin sols), are described in Sections 3-5.

The Campaign Implementation and Tactical Processes

The resulting campaign plan is then used to guide the Campaign Implementation and Tactical processes, which operate daily and produce activity plans (for the upcoming week and the immediate next plan to be uplinked, respectively) that account for rover resources (time of day, duration, power, data volume), requested science and engineering activities, and updated orbiter relays. At the end of each Tactical planning day, the plan is uplinked as a complete sequence bundle. As tactical plans execute, a sol-by-sol record of the executed campaign is documented, enabling comparison to the initial baseline sol path. A comparison of the executed campaigns to the initial baseline sol paths are described for each science campaign in Sections 3-5 and summarized in **Tables 2, 4, 5, and 6**.

3. The Crater Floor Campaign

Initial Campaign Plan

Perseverance landed at the Octavia E. Butler (OEB) landing site at the contact, or boundary, between two significant geologic units that would become the focus of the Crater Floor campaign: the Máaz formation and the Séítah formation **(Figure 2)**. These crater floor units are widespread within Jezero crater and have been linked to units in the ancient terrains outside of Jezero crater [7,9,10].

An out-and-back traverse was conceived for this first science campaign, intended to serve both scientific and engineering purposes [7]. Perseverance would traverse south and west from the OEB landing site in order to access the most scientifically compelling exposures of the Máaz formation, the Séítah formation along Artuby ridge (an escarpment near the contact of the Máaz and Séítah formations) **(Figure 2)**. The westward leg of the traverse along Artuby ridge would enable Perseverance to access the Séítah formation at one of the few locations that was likely traversable by the rover due to the rocky and sandy terrains throughout Séítah. Afterwards, Perseverance would retrace its steps and drive back to OEB, and then continue driving counterclockwise around the Séítah formation during a "rapid traverse" drive campaign to arrive at the Jezero fan front for the next campaign. Though longer, this counterclockwise path was favored over a more direct route to the fan for several reasons. A direct traverse toward the fan from South Séítah would require Perseverance to cross very rocky and sandy terrain of the Séítah formation in a series of short drives. Alternatively, the more benign Máaz formation could be traversed more quickly using Perseverance's Autonav capabilities [2,4]. The out-and-back traverse would also allow the Science Team to perform reconnaissance during the out-trip before deciding on sampling locations during the back-trip [6,12]. Practically, this traverse also helped accommodate the rover's commissioning schedule, which was not fully completed in the first 99 sols [1]. Capabilities such as Autonav and sampling [2,13] were not yet fully released, so exploration during the out-trip would make more efficient use of time while these capabilities became ready for use.

The Crater Floor campaign was thus allocated a total of 248 sols **(Table 2)**, and 64 sols were estimated for the rapid traverse drive campaign that would be largely dedicated to driving with minimal science activities. Of the 248 sols for the science campaign, 51 were estimated to be constrained sols (i.e. assumed to be not campaign-advancing). Twenty-three sols were estimated to be needed for solar conjunction, and another 23 sols were held as engineering margin (approximately 15% of useful sols).

The remaining 151 sols were distributed between sampling, drive, science, and engineering sols. With the allocation of four paired samples, or eight total cores, to the Crater Floor campaign, and the acquisition thereof estimated at 11 sols per sample pair, 44 sols were allocated for sampling. Of the 151 sols, 72 were estimated to be drive sols. Nineteen sols were allocated as dedicated science sols. The remaining 16 sols were allocated to finishing commissioning activities or updating the rover flight software. More details about the planning process and execution of the Crater Floor campaign are described in [7].

Executed Campaign

The Crater Floor science campaign took 32 sols longer to execute than originally planned, completing on sol 378 instead of sol 346 **(Table 4).** During the campaign, the team encountered unexpected delays during commissioning and first-time events, including sampling, that resulted in the exceedance of the 15% engineering margin. Several first-time events simply took longer to execute than expected, and some commissioning activities (e.g., first use of abrasion and sampling) relied on close coordination with validation efforts in the testbeds at the Jet Propulsion Laboratory, which contributed to schedule delays.

Drives

Drives estimates differed from predicted estimates throughout the campaign; the number of drive sols needed was underestimated during the beginning of the campaign but overestimated as drive capabilities were released throughout the campaign. Discrepancies between estimated and actual drive distance are expected, as drive estimates assume the ability to cover a certain amount of distance per sol, depending on the complexity of the terrain, but the actual drives are also dependent on rover resource constraints such as time allowed for driving, energy usage, etc., which change on a daily basis with the timing of orbiter relays and other activities in the plan. Underestimation of the drive distance achievable each sol at the beginning of the campaign was due to acclimating to a new rover mobility system as well as unfamiliar terrain. Although Perseverance's mobility system is substantially improved from its predecessor, the Curiosity rover, initial performance in the new Jezero terrains still had to be assessed in the early days of the mission. As Autonav capabilities were released after sol 129, executed drives better matched or exceeded estimated drives [2]. Towards the end of the campaign, especially during the return traverse from South Séítah to OEB, the combination of Autonav and existing terrain mesh over benign terrain allowed Perseverance to traverse ~1.7 km in 9 drive sols, instead of the 22 drive sols it took to cover the same distance during the initial out-trip. These benefits were also realized during the subsequent Rapid Traverse drive campaign from OEB to the base of the delta, during which it took 31 sols to cover 5 km instead of the predicted 64 sols [3,4].

Sampling

Unexpected events during the first sampling attempt also delayed the campaign timeline. Perseverance's first sampling attempt was made on Sol 164 at the Roubion target from the Máaz formation, but resulted in an empty sample tube, save for a few grains of regolith. Without an immediately obvious explanation for the absence of a rock core, the team decided to continue along the campaign path while the engineers assessed reasons for the sampling setback. Eventually it was deemed likely that the Roubion rock was too weak and disintegrated upon coring [7,10]; a stronger rock at Citadelle was thus selected for the next sampling attempt **(Figure 2)**. After modifying the sampling sol path to add additional sols to guarantee that core acquisition could be verified before irreversibly sealing the tube, two cores were successfully acquired at Citadelle.

Activities at South Séítah were prolonged due to splitting abrasion and sampling activities over solar conjunction and a flight software update. The mission also encountered delays while sampling the Séítah formation. At the first Séítah sampling site, a few faults occurred during the abrasion and sampling activities, as well as DSN outages that precluded uplinking of plans. Ultimately, abrasion and sampling were successful after 29 sols **(Table 4)**, compared to the predicted

Baseline Campaign Leg	Start Sol	End Sol	# Sols	Actual Campaign Leg	Start Sol	End Sol	# Sols
				Drive to Imaging Point	99	118	19
				Science at Imaging Point	118	122	4
Drive to Séítah-North	99	115	16	Drive to Séítah-North	122	128	6
Science at Séítah-North	115	116	1	Science at Séítah-North	128	129	1
Drive to Polygon Valley	116	130	14	Drive to Polygon Valley	129	138	9
Science at Polygon Valley	130	135	5	Science at Polygon Valley	138	153	15
				Drive to Máaz sampling site	153	157	4
Sample Máaz - pair 1	135	148	13	Sample Máaz (unsuccessful)	157	168	11
				Drive to Artuby	168	177	9
				Science at Artuby	177	178	1
Drive to Citadelle	148	156	8	Drive to Citadelle	178	180	2
				Sample Máaz - pair 1	180	199	19
Drive to South Séítah	156	165	9	Drive to South Séítah	199	204	5
Science at South Séítah	165	171	6	Science/Abrasion at South Séítah	204	210	6
				Drive to Séítah sampling site 1	210	211	1
				Conjunction Preparation	211	217	6
				Conjunction	217	236	19
				Post-Conjunction activities	236	237	1
				Drive to Séítah sampling site 1	237	240	3
				Prep for FSW update	240	243	3
				FSW Update	243	246	3
				Post-FSW activities	246	248	2
Sample Séítah - pair 2	171	190	19	Sample Séítah - pair 2	248	277	29
				Science at South Séítah	277	280	3
				Drive to Séítah sampling site 2	280	286	6
Sample Séítah - pair 3	190	200	10	Sample Séítah - pair 3	286	340	54
				Drive back to Artuby	340	343	3
Drive back to Citadelle	200	209	9				
Drive to Mont Rocheforte	209	217	8				
Conjunction	217	236	19				
Finish drive to Mont Rocheforte	236	237	1				
Science at Mont Rocheforte	237	240	3	Science/Abrasion at Artuby	343	350	7
Sample Mont Rocheforte - pair 4	240	253	13				
Drive to OEB	253	273	20	Drive to OEB	350	362	12
				Sampling at OEB	362	378	16

Table 4. Comparison of the baseline campaign legs versus the actual campaign legs for the Crater Floor campaign. Green cells indicate drives, yellow cells indicate science sols, orange cells indicate sampling events, and grey cells indicate engineering events. Rows between the baseline and actual campaign legs are matched according to common events to better enable comparison between the baseline and actual events. Note that the end date of the baseline path differs from the baseline end date reported in Table 2 because unallocated and margin sols were bookkept at the end of the baseline sol path.

nominal 11 unconstrained sols. While acquiring the second pair of Séítah samples, pebbles became lodged in the bit carousel. Recovering from this anomaly took significant discussion and work by the Engineering Team over the course of several weeks [4]. Eventually the pebbles were successfully dislodged, and the Science Team decided to discard the acquired core (due to possible contamination and volatile loss during the anomaly recovery efforts) and reposition the rover to finish sample acquisition. Resolution of this anomaly, abrasion, and eventually successful sampling, ended up taking 54 sols, compared to the predicted nominal 11 unconstrained sols to collect a sample pair.

Science Decisions

Science decisions made during the executed crater floor campaign also varied from the initial campaign plan, by design, as new observations influenced changing science priorities **(Table 4)**. One such example was Artuby ridge, which was observed from a distance early in the campaign to contain layering [7]. This motivated further study of Artuby ridge, including dedicated science sols to perform remote sensing and abrasion on these layers. In order to keep within the allotted campaign timeline, the Artuby investigation replaced the originally planned traverse to Mont Rochefort, a network of positive-relief fractures that were hypothesized to contain mineralized fracture fill. However, long-distance observations from Perseverance and Ingenuity showed minimal outcrop [7]. The fourth sample pair allocated to the Crater Floor campaign, initially intended for Mont Rocheforte, was then reallocated to a second sample pair from the Máaz formation, which was later collected in the vicinity of the Octavia E. Butler Landing site.

Impacts for the Next Campaign

Lessons learned from the first science campaign on the Crater Floor were synthesized and carried forward into planning for Perseverance's second science campaign at the fan front. The initial assumption to allot 15% of useful sols for engineering margin was increased to 30% for the fan front campaign based on the performance from the crater floor campaign (41% fault rate; **Table 2**).

Several new capabilities and operational changes would also affect planning for the next campaign. For example, during the Crater Floor campaign, the Mars 2020 mission transitioned from operating 7 days a week to 5 days a week, which would increase the percentage of constrained sols in subsequent campaigns. However, several new capabilities counteract this change. Multi-sol driving capabilities would allow the rover to drive on subsequent days over a multi-sol plan; previously the second and/or third sols of a multi-sol plan would not be considered Useful sols, as the rover would have to remain stationary until the results of the first sol's drive was known. Multi-sol driving allows the second and/or third sols of a multi-sol plan to contain campaign-advancing drives and cover more distance. Efficiency improvements due to the new multi-sol driving capability were apparent during the rapid traverse drive campaign from OEB to the fan front. Similarly, the new ability to execute both proximity science and driving in the same plan would also help turn previously unproductive/constrained sols into sol-path-advancing sols. With nine sampling events executed during the crater floor campaign, confidence in the rover's sampling mechanics also improved and fewer sols were bookkept in the sampling sol path.

4. THE FAN FRONT CAMPAIGN

Initial Campaign Plan

At this point in the mission, the project determined that exploration of the Jezero fan would be split between a Fan Front campaign, which would explore the lower portions of the fan adjacent to the crater floor, and an Upper Fan campaign, which would climb the fan to investigate its top surface **(Figure 1)**. Part of this decision was motivated by the desire to deposit an initial sample depot by the end of the prime mission (sol 669 on January 6, 2023), and that which contained important samples from the fan.

The Fan Front campaign was thus conceived to explore the stratigraphy exposed along the scarps of the fan front, which were originally hypothesized to represent the distal lake layers with a high likelihood of preserving biosignatures if any were present. Exploration along the fan front would also investigate the contact between the fan sediments and the crater floor, as this relationship would be critical for determining which unit was deposited first and, with potential sample return, could help constrain the age of the fan deposits relative to the crater floor unit. Two prime locations were identified for this investigation where the rover could traverse fan stratigraphy up to the upper fan: Hawksbill Gap and Cape Nukshak **(Figure 3)**. Though high-resolution data of either of these locations was lacking during campaign planning, the team decided to baseline the route up Hawksbill Gap based on existing long-distance imaging. The initial campaign route would take Perseverance to the base of Cape Nukshak, during which the rover could acquire reconnaissance imaging of both Hawksbill Gap and Cape Nukshak to assess the quality and contiguity of outcrop at both locations. At that point, the team would decide whether to ascend the delta via Hawkbill Gap or Cape Nukshak. In the baseline scenario, Perseverance would ascend the delta via Hawksbill Gap, stopping periodically to perform remote sensing and abrasion activities during the ascent to understand variations in stratigraphy and lithology. Perseverance would then descend back down to the crater floor in preparation for depositing the sample depot, and could acquire up to three sample pairs depending on the science results acquired during the ascent. At the conclusion of the Fan Front campaign, Perseverance would deposit the first, smaller depot of 10 sample tubes at Three Forks, containing samples from both the crater floor and fan front.

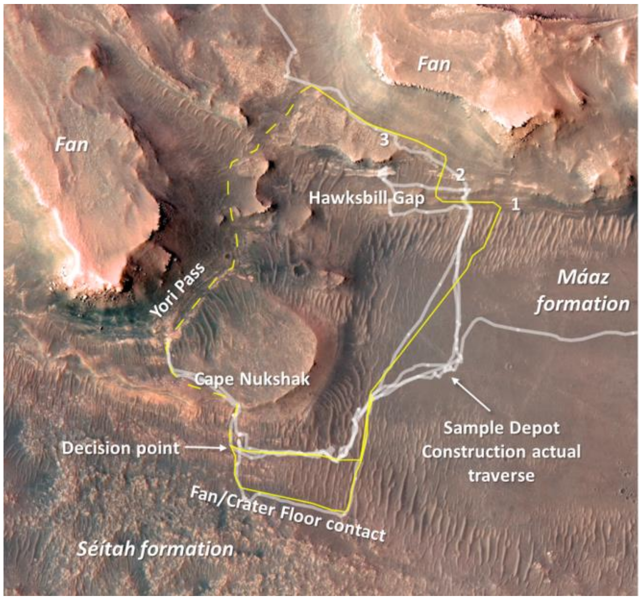

Figure 3. Comparison of the planned traverse for the Fan Front campaign (yellow; solid lines indicate the Hawksbill Gap baseline ascent path and dashed lines indicate the alternate Cape Nukshak ascent path), and Perseverance's actual drive path (white). Landmarks referenced in the text and in Table 5 are labeled.

A total of 242 sols were allocated for the Fan Front campaign, corresponding to an estimated 92 constrained sols (associated with operating only five times a week) **(Table 2)**. Following the increased engineering margin policy resulting from the Crater Floor campaign, 32 sols were held as engineering margin (30% of useful sols). With three sample pairs, or six total cores, as well as the sealing of one witness tube allocated to the Fan Front campaign, 31 sols were allocated towards sampling sols. Strategic route planning efforts estimated that 38 drive sols would be needed. With the expectation that this would be the first time the team would encounter definitive sedimentary rocks in Jezero crater, a substantial 31 sols were allocated towards science sols, including time for up to five abrasion opportunities (initially unassociated with sampling, taking 4-5 sols per abrasion [11]) to better understand the lithologies of the fan front rocks. Five sols were allocated to rover flight software updates anticipated during the timespan of the campaign, and ten sols were allocated for other engineering activities.

Executed Campaign

The Fan Front science campaign ended on sol 707 instead of the predicted sol 652, but with the insertion of the Sample Depot Construction campaign (51 sols) towards the end of the science campaign, the science campaign itself took 246 sols to execute, which is comparable to the predicted 242 **(Table 2, Table 5)**. Perseverance also ended up collecting nine samples in total, instead of the six initially allotted to the campaign.

Sampling and Science Decisions

Obvious differences between the baseline and actual Fan Front campaign **(Table 2)** are that fewer science sols were used during the actual campaign, corresponding to an abbreviated version of the Hawksbill Gap ascent and descent strategy to collect abraded and remote science along that traverse, and that more samples were acquired than initially planned. These differences were due to difficulties encountered during the first abrasion attempts at the beginning of the campaign, and changing schedule pressures as unexpected anomalies and the sample depot construction strategy evolved.

The first attempts to abrade fan front rocks at Sunset Hill and Hogwallow Flats resulted in fractured rocks that did not provide sufficiently flat surfaces on which the proximity science instruments could be placed. Another complication observed during these early abrasion attempts was that the fan front rocks encountered thus far were usually not spatially large enough to support the creation of an abrasion patch as well as a coring location. At Skinner Ridge, the team encountered a layered sandstone rock with enough surface area for both abrasion and potential sampling. The first sample pair from the fan front was thus acquired at Skinner Ridge, and a witness tube was also sealed shortly thereafter. The acquisition of the second sample pair at Wildcat Ridge was itself comparatively uneventful, but after concluding sampling activities, the team observed Foreign Object Debris (FOD) in the drill bit and bit carousel. Perseverance then remained stationary for 16 sols while the Engineering Team diagnosed the FOD anomaly and eventually planned activities that would eject the FOD.

The Science Team subsequently decided to drive back to Cape Nukshak, where observations were previously made during the initial legs of the Fan Front campaign and interest in these rocks increased as they may be laterally equivalent to the rocks encountered at Hawksbill Gap. At Cape Nukshak, a third pair of samples was acquired, but the team encountered a tube sealing fault that resulted in the second tube (named Mageik) not being sealed until 40 sols after sample acquisition, during the regolith sampling campaign. Another witness tube was processed after this sampling event.

By this point in the campaign, it was decided that Perseverance would also acquire a pair of regolith samples, previously unallocated in the baseline campaign plan. One of the regolith sample pair would be intended for the sample depot to be deposited before the end of Perseverance's prime mission. The team decided to acquire the regolith sample pair at a dune named Observation Mountain, near Cape Nukshak, and proceeded to acquire the requisite science observations. However, the mission decided to not acquire and seal the first regolith sample until the Mageik sample, still unsealed at this point, could be sealed successfully. While the Engineering Team assessed methods to improve chances of sealing Mageik, the Science Team decided to drive up Cape Nukshak to Yori Pass **(Figure 3)** to explore rocks that could be

Baseline Campaign Leg	Start Sol	End Sol	# Sols	Actual Campaign Leg	Start Sol	End Sol	# Sols
Drive to Decision Point along Fan/Crater Floor contact	411	422	11	Drive to Decision Point along Fan/Crater Floor contact	411	421	10
				Science at Decision Point	421	426	5
Drive to Hawksbill Gap stop 1	422	438	16	Drive to Hawksbill Gap stop 1	426	449	23
Science/Abrasion at Hawksbill Gap stop 1	438	447	9	Science/Abrasion at Hawksbill Gap stop 1 (Sunset Hill) - incomplete	449	456	7
Drive to Hawksbill Gap stop 2	447	449	2	Drive to Hawksbill Gap stop 2	456	463	7
Science/Abrasion at Hawksbill Gap stop 2	449	461	12	Science at Hawksbill Gap stop 2 (Hogwallow Flats)	463	464	1
Drive to Hawksbill Gap stop 3	461	463	2				
Science/Abrasion at Hawksbill Gap stop 3	463	464	1				
FSW Update	464	473	9	FSW Update	464	470	6
Resume Science/Abrasion at Hawksbill Gap stop 3	473	490	17	Science/Abrasion at Hawksbill Gap stop 2 (Hogwallow Flats) - incomplete	470	474	4
Drive to Hawksbill Gap stop 4	490	492	2	Drive to Hawksbill Gap stop 2.5	474	476	2
Science/Abrasion at Hawksbill Gap stop 4	492	502	10	Science at Hawksbill Gap stop 2.5 (Betty's Rock)	476	477	1
Drive to Hawksbill Gap stop 5	502	509	7				
Science/Abrasion at Hawksbill Gap stop 5/sampling site 1	509	523	14				
Seal Witness Tube	523	524	1				
Sample Fan Front - pair 1	524	537	13	Sample at Hawksbill Gap stop 3 (Skinner Ridge) - pair 1	477	499	22
				Seal Witness Tube 1	499	501	2
Descend to Hawksbill Gap sampling site 2	537	545	8	Drive to Hawksbill Gap stop 4	501	502	1
Sample Fan Front - pair 2	545	565	20	Sample at Hawksbill Gap stop 4 (Wildcat Ridge) - pair 2	502	519	17
Descend to Hawksbill Gap sampling site 3	565	572	7	Foreign Object Debris Investigation	519	535	16
				Drive to Cape Nukshak	535	557	22
Sample Fan Front - pair 3	572	591	19	Sample at Cape Nukshak (Enchanted Lake) - pair 3	557	584	27
Drive to Regolith sampling location	591	598	7				
				Seal Witness Tube 2	584	592	8
				Sample Regolith pair - part 1	592	606	14
				Drive to Yori Pass	606	609	3
				Sample at Yori Pass (Hidden Harbor) - single sample	609	629	20
Science at Regolith sampling location	598	599	1	Drive back to Regolith sampling location	629	633	4
Sample Regolith pair	599	618	19	Complete sampling of Regolith pair	633	642	9
Drive to Sample Depot area	618	619	1	Sample Depot Construction	642	693	51
				Drive to White Rocks	693	707	14

Table 5. Comparison of the baseline campaign legs versus the actual campaign legs for the Fan Front campaign. Green cells indicate drives, yellow cells indicate science sols, orange cells indicate sampling events, and grey cells indicate engineering events. Rows between the baseline and actual campaign legs are matched according to common events to better enable comparison between the baseline and actual events. Note that the end date of the baseline path differs from the baseline end date reported in Table 2 because unallocated and margin sols were bookkept at the end of the baseline sol path.

laterally equivalent to Hogwallow Flats. At Yori Pass, Perseverance was finally successful in sealing the Mageik sample tube, just in time for the team to acquire a single sample of the Yori Pass rocks, which would not be intended for the upcoming first sample depot to be deposited at Three Forks. Perseverance then returned back to Observation Mountain to acquire the two regolith samples.

Sample Depot Construction

The Fan Front campaign was also modified during execution to accommodate the evolving strategy for the construction of the first sample depot. In coordination with the Mars Sample Return mission, Perseverance helped conduct reconnaissance imaging of Three Forks to assess surface conditions at the sample depot location at the beginning of the Fan Front campaign. With the depot to be deposited on the crater floor at Three Forks, Perseverance would need to traverse through the fan front again in order to ascend the fan to begin the Upper Fan campaign. Thus, after the 51 sols spent depositing the 10 sample tubes at Three Forks **(Table 5)**, Perseverance drove north from the sample depot location up to Rockytop, after which the Fan Front campaign ended and the Upper Fan campaign commenced.

Impacts for the Next Campaign

The fault rate for the Fan Front campaign (41%) was more consistent with the assumed engineering margin (30%) than it was for the Crater Floor campaign (15%), thus it was deemed appropriate to carry forward the 30% engineering margin to the Upper Fan campaign. The sols spent on resolving the FOD and sealing anomalies were regained by the operational efficiencies (e.g., multisol driving and reduced ground-in-the-loop cycles in the sampling sol path) realized towards the end of the Crater Floor campaign. In addition, though the Mars 2020 mission continued to operate at 5 days a week, increasing the number of constrained sols compared to operating 7 days a week, the mission made ongoing efforts to reduce the timeline of the Tactical and Campaign Implementation shifts, which would decrease the overall number of constrained sols by allowing more planning cycles.

5. THE UPPER FAN CAMPAIGN

Initial Campaign Plan

The Upper Fan campaign would start at the Rockytop outcrop where the Fan Front campaign ended, and would end at the margin unit at a location named Mandu Wall, where the next Margin campaign would commence **(Figure 4)**. The strategic traverse between these two endpoints would take the rover through exposures of 1) light-toned fractured bedrock (Jenkins Gap), 2) the curvilinear unit (at a location later named Tenby), 3) hypothesized conglomerates at Castell Henllys, 4) a potential detection of hydrated silica (a mineral group with high potential to preserve biosignatures if present) at Foel Drygarn, and 5) Fall River Pass, assumed to be the youngest fan deposit Perseverance would encounter along this traverse. Dedicated science investigations would be

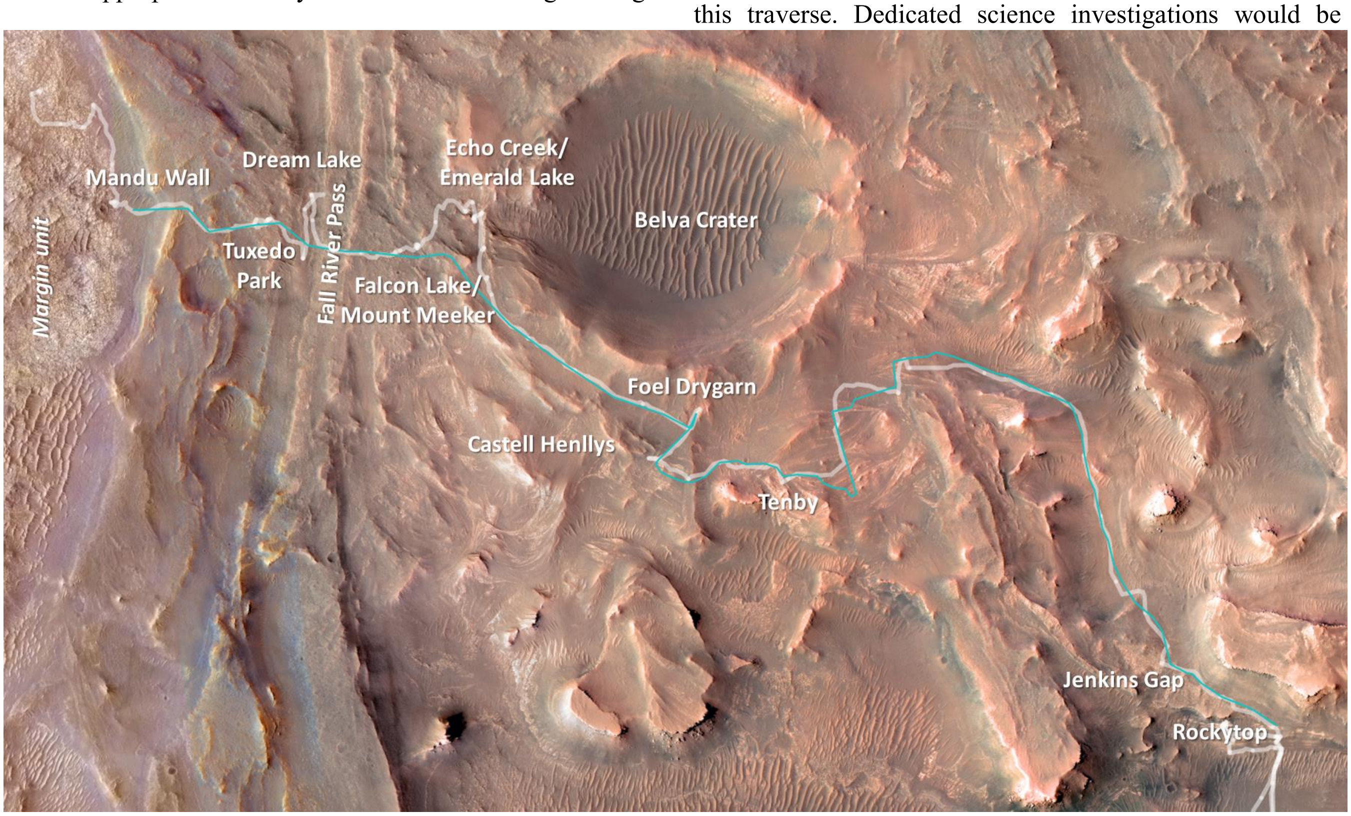

Figure 4. Comparison of the planned traverse for the Upper Fan campaign (cyan) and Perseverance's actual drive path (white). Landmarks referenced in the text and in Table 6 are labeled.

performed at each of these five locations, and sampling of up to four samples would occur if these lithologies were determined to be compelling additions to Perseverance's on-board sample collection.

Using similar assumptions as for the Fan Front campaign, the Upper Fan campaign was allocated 237 sols in total **(Table 2)**. Of these 237 sols, 99 sols were estimated to be constrained. Thirty-five sols (~32% of useful sols) were designated as engineering margin. In contrast to previous campaigns, the successful construction of the sample depot at Three Forks meant that Perseverance would now only collect single samples of unique rock lithologies at each sampling workspace, rather than the paired sampling strategy leading up to the Three Forks sample depot. Thus, four single samples were allocated to the Upper Fan campaign, resulting in an assumption of 32 sampling sols based on an updated single sampling sol path [11]. An additional 24 sols were designated as science sols, including opportunities to perform abrasions on new lithologies without an assumption of sampling. Forty-one drive sols were estimated to complete the strategic traverse through the Upper Fan. Five sols were allocated to rover flight software updates that would happen during this campaign, and five additional sols were allocated for other engineering activities.

Executed Campaign

The overall campaign ended on Sol 910, 34 sols earlier than the anticipated Sol 944, in large part because only three samples were acquired rather than the four initially allocated. The drives to Tenby outperformed estimates **(Table 6)** due to multisol driving and not needing to expend science sols to make observations of the terrains Perseverance was driving through, as science activities could be added to the drive sols at relatively little resource cost. Perseverance then collected a sample of the curvilinear unit at Tenby as baselined. The search for conglomerates at Castell Henllys was aided by reconnaissance observations from both Ingenuity and Perseverance, but ultimately the rocks there were determined to not be the conglomerates that the Science Team had hypothesized. Perseverance then drove to Foel Drygarn to investigate the source of a potential hydrated silica detection from orbital observations, however closer inspection by the rover instruments did not identify hydrated silica and Perseverance moved on without acquiring a sample. Perseverance continued on the strategic drive path but took a detour to Echo Creek to take a closer look at the stratigraphy along the edge of Belva crater, which was not an initially planned stop. The team did observe conglomerates at Echo Creek and proceeded to perform science and abrasion activities and eventually collect a sample at Emerald Lake, although several delays were encountered due to rover positioning and the initial rock target crumbling during a sampling attempt.

Perseverance then took another previously unplanned detour to Falcon Lake to investigate several boulder candidates for potential abrasion and sampling. The interest in investigating boulders evolved during the campaign as a sample of such a boulder could represent materials brought from the Jezero watershed and deposited in some of the fan's youngest deposits. After investigating several boulders, a decision was made to sample the Mount Meeker boulder, which appeared compositionally distinct (and richer in pyroxene) compared to other boulders and previous rock targets. However, the Mount Meeker boulder was significantly harder than previous rock targets, which precluded successful coring. Thus, the decision to sample a boulder was put on hold until more assessment could be done by the Engineering Team to determine how to successfully core harder rock targets. In the meantime, images from the Ingenuity helicopter showed interesting outcrops hypothesized to contain carbonate in the Dream Lake vicinity, past the originally planned stop at Fall River Pass. The team therefore decided to bypass Fall River Pass and investigate the rocks at Dream Lake, resulting in the collection of a sample there.

Impacts for the Next Campaign

The boulder sample that could not be acquired during the Upper Fan campaign was carried forward to the Margin campaign, as more boulders were expected to be encountered in that campaign. The fluidity in sampling decisions made during all three of Perseverance's science campaigns thus far also resulted in implementing a more flexible sol path planning strategy for the Margin campaign, where multiple Margin campaign end dates were estimated depending on whether 3-5 samples would be acquired. The origin of the Margin unit was highly uncertain compared to the Fan Front and Upper Fan units, which were known to be sedimentary deposits. In contrast, the Margin unit could be igneous (like the Séítah unit) or a sedimentary unit of varying origins. Given this uncertainty, it would not be clear how many samples to allocate to the Margin campaign, thus a notional number of 3-5 samples was designated to provide flexibility based on early discoveries anticipated in the Margin campaign.

The fault rate for the Upper Fan campaign (46%) held relatively constant compared to the previous Fan Front campaign (41%), thus the assumption of 30% engineering margin would continue to be applied to the next Margin campaign plan. Operational efficiencies such as multisol driving and more efficient sampling sol paths continued to add productive sols towards advancing the campaign compared to the beginning of the mission. Later drives during the Upper Fan campaign, particularly in the rougher terrains at Tuxedo Park, also helped inform the anticipated drive progress during the upcoming Margin campaign, which was anticipated to have similarly rough terrain.

Baseline Campaign Leg	Start Sol	End Sol	# Sols	Actual Campaign Leg	Start Sol	End Sol	# Sols
Drive to Jenkins Gap	708	714	6	Drive to Jenkins Gap	708	711	3
Science at Jenkins Gap	714	716	2	Science at Jenkins Gap	711	713	2
Drive to Tenby	716	750	34	Drive to Tenby	713	734	21
Science at Tenby	750	755	5				
Sample at Tenby	755	772	17	Sample at Tenby	734	753	19
Science at Foel Drygarn	772	777	5				
Drive to Castell Henllys	777	789	12	Drive to Castell Henllys	753	755	2
Science at Castell Henllys	789	795	6	Science at Castell Henllys	755	757	2
Sample at Castell Henllys	795	815	20				
Science of Foel Drygarn	815	818	3				
Drive to Foel Drygarn	818	823	5	Drive to Foel Drygarn	757	761	4
Science at Foel Drygarn	823	825	2	Science at Foel Drygarn	761	762	1
				Drive to Echo Creek	762	772	10
				Science at Echo Creek	772	784	12
Sample at Foel Drygarn	825	849	24	Sample at Emerald Lake	784	836	52
Drive to Mount Julian	849	860	11	Drive to Falcon Lake	836	843	7
Science of Belva Crater	860	863	3	Science at Falcon Lake	843	856	13
				Sample attempt at Mount Meeker (unsuccessful)	856	866	10
				Drive to Dream Lake	866	872	6
Drive to Fall River Pass	863	867	4	Sample at Dream Lake	872	885	13
				Drive to Fall River Pass	885	886	1
				Science at Fall River Pass	886	890	4
Science at Fall River Pass	867	874	7	FSW Update	890	894	4
Sample at Fall River Pass	874	894	20	Science at Fall River Pass	894	896	2
Drive to Mandu Wall	894	907	13	Drive to Mandu Wall	896	910	14

Table 6. Comparison of the baseline campaign legs versus the actual campaign legs for the Upper Fan campaign. Green cells indicate drives, yellow cells indicate science sols, orange cells indicate sampling events, and grey cells indicate engineering events. Rows between the baseline and actual campaign legs are matched according to common events to better enable comparison between the baseline and actual events. Note that the end date of the baseline path differs from the baseline end date reported in Table 2 because unallocated and margin sols were bookkept at the end of the baseline sol path.

6. SUMMARY

Through more than 900 sols of operations on the surface of Mars, the Perseverance rover has collected a robust record of how strategically developed plans and schedules compare to the actual activities executed on Mars. Lessons learned from each of Perseverance's first three science campaigns have been collected and fed forward into the planning of the subsequent campaign, improving our strategic allocation of resources and schedule. As science campaigns execute, the mission has learned to increase its assumption of the proportion of margin sols needed to account for unexpected faults or events, from an initial 15% at the beginning of the Crater Floor campaign to a steadier 30% for the Fan Front and Upper Fan campaigns. Although unexpected events, such as sampling and sealing faults, and external schedule pressures, such as the timing of Earth-based testing of commissioning events during the Crater Floor campaign and accommodating sample depot-related requests from the Mars Sample Return campaign during the Fan Front campaign, contributed to schedule delays, several efficiency improvements helped counteract these effects. For example, our understanding of rover mobility and its performance on the variety of Jezero terrains improved over time, enabling better predictions of drive times throughout the campaigns. Despite moving from 7-days-a-week operations to 5-days-a-week operations during the Crater Floor campaign, which increases the number of constrained sols, ongoing efforts to decrease the operational timeline helped to return some of these sols to unconstrained sols. New rover capabilities such as multisol driving and reduction of ground-in-the-loop in the sampling sol path have also improved campaign productivity relative to the beginning of the mission. In general, the proportion of campaign-advancing sols has increased with each campaign.

Perseverance will continue to apply these methods towards future science campaigns and compare the strategic campaign plans with the actual executed campaigns. Continued feedback between the strategic and tactical processes will continue to improve our predictive mission planning abilities on Mars 2020, resulting in more accurate resource allocation during campaign planning and enabling Perseverance to prepare and react to the evolving needs of the Mars Sample Return campaign. Results from Perseverance's experiences will also help inform strategic mission planning for other future planetary missions.

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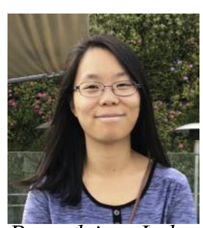
BIOGRAPHY



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