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The Mars 2020 Candidate Landing Sites: A Magnetic Field Perspective

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Key Points:

- Mars 2020 offers the opportunity to acquire samples that record the intensity and direction of the ancient Martian magnetic field
- Laboratory paleomagnetic measurements of returned samples can address questions about the history of the Martian dynamo, thermal evolution, and climate
- We recommend Northeast Syrtis as preferred site for magnetic investigations, followed by Columbia Hills and Jezero

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Abstract We present an analysis of the remaining three candidate landing sites for Mars 2020, Columbia Hills (CH), Northeast Syrtis (NES) and Jezero (JE) from the perspective of understanding Mars' crustal magnetic field. We identify how the different sites can address each of six community-defined paleomagnetic science objectives for Mars return samples. These objectives include understanding the early dynamo field and its variability, identification of magnetic minerals that carry magnetization in the samples, and characterization of any thermal and chemical alteration of samples. Satellite data have provided global and regional constraints on crustal magnetization, indicating strong magnetizations at CH and weak to no magnetization at JE and NES. However, the primary paleomagnetic interest—understanding the early dynamo—requires ground truth from a landing site at which pre-Noachian and Early Noachian deposits are accessible. This requirement is most likely met by the site NES, which contains meggabreccia deposits, and it is therefore the highest priority landing site for magnetic field investigations. Importantly, a sample return mission has never been done, and so any of the three landing sites will provide critical, new data that will contribute to understanding the history of Mars' magnetic field and crustal mineralogy and, in turn, yield constraints on the planet's evolution.

Plain Language Summary Mars 2020, a mission to Mars, will for the first time collect rock samples for subsequent return to the Earth. Here we evaluate how each of the last three candidate landing sites can shed light on the Martian magnetic field and its history. We evaluate which landing site is best suited to address each of six science objectives regarding the origin, variability, and evolution of the magnetic signatures on Mars. We first summarize what is known about magnetization around the landing sites based on satellite data. Because we are primarily interested in the history of the magnetic field, an ideal site should offer ancient (~4 billion years old and older) accessible outcrops that might be recorders of Mars' ancient global magnetic field. We combine current knowledge about the surface age, geology, and magnetic field, and chose Northeast Syrtis as the preferred landing site, followed by Columbia Hills and Jezero. However, any of the three sites will provide us with new data that will contribute to understanding Mars' magnetic field history and, in turn, its evolution.

1. Introduction

The Martian magnetic field is unique among the planets in our solar system. Satellite magnetometry measurements at Mars in the 1990s revealed strong crustal fields (Acuna et al., 1999). Their sources are magnetic minerals in the crust that were likely magnetized by an ancient global dynamo field that was active until about 4 billion years ago (Lillis et al., 2013; Vervelidou, Lesur, Grott, et al., 2017). The strongest crustal fields are concentrated in the southern hemisphere, where they exceed the Earth's lithospheric field strength by an order of magnitude at orbital altitudes (Purucker et al., 2000). Explanations for such strong and localized fields have been widely discussed; strong remanent magnetizations and/or a thick magnetized layer are typically invoked (Connerney et al., 1999; Langlais et al., 2004), but no consensus has been reached as to the underlying magnetization mechanism. Additionally, the origin, strength, and temporal decline of the ancient dynamo field are poorly constrained. Paleomagnetic measurements of samples, selected by the Mars 2020 rover mission and subsequently returned by a downstream mission, could revolutionize our understanding of the ancient dynamo field, that in turn is coupled to the evolution of the planet's interior (Kuang et al., 2008), tectonic history (Stevenson, 2001), and climate (Jakosky & Phillips, 2001).

Magnetic field data have primarily been collected by satellites, particularly the Mars Global Surveyor (MGS) and Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft. A further source of magnetic field information is the ancient and strongly magnetized Martian meteorite, ALH 84001, which suggests that a dynamo with an Earth-strength field was active at, or before, 4 Ga (Weiss et al., 2002). Other Martian meteorites, that is, the shergottite, nakhlite, and chassignite meteorites, provide insight into the formation and intrinsic magnetic properties of Martian rocks (Rochette et al., 2005) and indicate that the dynamo had declined to no more than ∼1 μT at 1.3 Ga (e.g., Collinson, 1997; Funaki et al., 2009). Because these Martian meteorites could have been magnetized by a crustal remanent field rather than an active dynamo, the results only require that a dynamo existed at, or prior to, the timing of magnetization acquisition. The InSight Lander will be the first mission to measure the magnetic signal at the planetary surface (Banerdt et al., 2013). Its measurements will however be limited to the landing location. The upcoming sample return mission Mars 2020 offers a unique chance to sample magnetized rock from the surface of Mars with geological context, sample orientation, and, after the samples are returned, precise radiometric ages.

The mission objectives for Mars 2020 are focused on investigating Mars as potential habitat for past or present life (Mustard et al., 2013). Magnetic studies contribute to such investigations because a global magnetic field can provide conditions favorable for life as we know it (Ehlmann et al., 2016; Rochette et al., 2006; Weiss et al., 2018). Mars has lost most of its atmosphere throughout its history, possibly related to the cessation of its global dynamo field, which may have facilitated atmospheric erosion by the solar wind (Dehant et al., 2007). The cessation of the dynamo is typically cited as ∼4.05–4.1 Ga (Lillis et al., 2008, 2013; Vervelidou, Lesur, Grott, et al., 2017), although later/longer-duration dynamos have been proposed (Langlais & Purucker, 2007; Schubert et al., 2000; Milbury et al., 2012). In particular, if the coherence length-scale of the magnetization in younger regions is below the satellite resolution, there may be smaller regions of younger units with primary magnetizations acquired in a field that persisted after 4.1 Ga. Resolution of the magnetic surface field can be approximated by orbit altitude (Blakely, 1995), and the lowest satellite measurements to date are mostly at around 135-km altitude with a few measurements taken at ∼100-km altitude. Constraining the properties and the cessation of the dynamo with higher accuracy requires sampling of representative rocks formed during the pre-Noachian to Early Noachian, the period in which the dynamo most likely ceased. This presents a challenge to Mars 2020, as pre-Noachian materials are at best known to be exposed at very limited locations and over small spatial scales on Mars (Nimmo & Tanaka, 2005). Such materials may have undergone substantial thermal and chemical reworking over Mars' history.

Sample return will address long-standing questions regarding the nature and origin of crustal magnetization, which are fundamentally linked to the planet's early history and evolution (Weiss et al., 2018). In particular, the mechanisms responsible for magnetization acquisition and the mineral carriers are key unknowns. Ferro- and ferrimagnetic minerals can acquire natural remanent magnetization (NRM) when they are exposed to a magnetic field via thermal, chemical, and/or shock processes. These three mechanisms respectively result from (i) magnetic minerals cooling below their blocking temperature, (ii) alteration and magnetization during (re)crystallization, and (iii) shock during impacts. Magnetization measurements and age dating on actual samples will shed light on chronology of the dynamo field, and/or mechanisms of magnetization acquisition and/or removal. In contrast to meteorite samples, returned and oriented samples will allow the paleodirection of the ancient field to be inferred and provide samples unaffected by the shock associated with planetary ejection of meteorites, although possibly affected by shock associated due to impactors. Thus, laboratory measurements of sample magnetization will provide important constraints on magnetization models. Such models currently rely solely on satellite data that provide little to no information on short wavelength crustal fields. Furthermore, inferring the underlying magnetization from magnetic field measurements is an inherently nonunique inverse problem because only part of the underlying magnetization gives rise to the observable magnetic field (e.g., Gubbins et al., 2011; Maus & Haak, 2003; Runcorn, 1975).

The purpose of this paper is to review existing knowledge regarding the possible Mars 2020 landing sites Columbia Hills (CH), Northeast Syrtis (NES), and Jezero (JE), with a focus on suitability for obtaining samples that can shed light on the linked issues regarding magnetic field history and evolution, and crustal magnetization. In the following, we give a geologic overview and assess the final three candidate landing sites in the context of future magnetic investigation of returned samples. We briefly review recent global and regional models that provide constraints on magnetization and crustal field intensity at each site. We then summarize paleomagnetic sample return objectives and discuss what further knowledge could be gained using returned

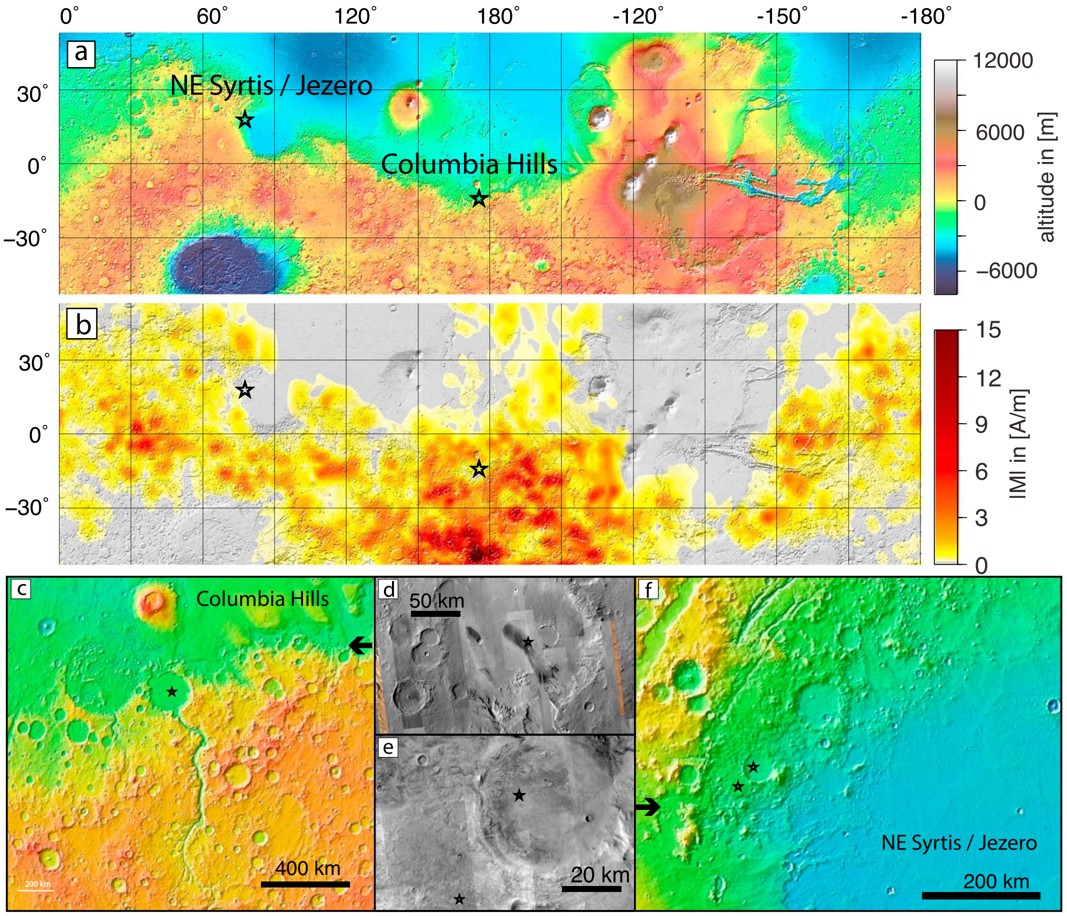

Figure 1. A (a) Mars Orbiter Laser Altimeter (MOLA) topography and (b) magnetization map (see section 3) to give context for MOLA and Mars Reconnaissance Orbiter Context Camera images of the landing site regions (c, d) Columbia Hills and (e, f) NE Syrtis and Jezero acquired from Google Mars. Note that NE Syrtis and Jezero plot on top of each other in (a) and (b). The altitude color bar applies to (a), (c), and (f). NE = Northeast.

samples. We evaluate each of the landing sites in the context of these objectives and rank the landing sites accordingly, noting that any of the three sites will provide important new information on Mars' magnetic field and crustal magnetization.

2. Local Geology

The final three candidates for the Mars 2020 landing site are CH (15° S, 176° E), NES (18° N, 77° E), and JE (18° N, 79° E) as shown in Figure 1. All landing sites are located along the global crustal dichotomy (Smith et al., 2001). NES and JE lie close to the western rim of the Isidis impact basin, and CH is within the Gusev impact basin and close to the former landing site of the Spirit rover. Figures 1c and 1d show the CH landing site location within Gusev crater. The rocks exposed at the surface of CH are thought to be Late Noachian-Early Hesperian volcanoclastic and possibly also evaporitic materials draped on topography and uplifted by the impact that formed Gusev or surrounding craters (McCoy et al., 2008; van Kan Parker et al., 2010). The area offers a variety of sampling possibilities because igneous units, as well as clays and carbonate-rich outcrops have been detected, that may be of hydrothermal (Filiberto & Schwenzer, 2013) or possibly even lacustrine origin (Morris et al., 2010; Ruff et al., 2014). The finding of opaline silica by Spirit, possibly the result of fumarolic sulfate leaching or hot spring silica precipitation (Ruff et al., 2011; Squyres et al., 2008) makes this landing site an interesting candidate.

The two landing sites NES and JE in the Nili Fossae region are not distinguishable on a global scale as they are only 37 km apart (Figure 1a). The JE landing site is within JE crater, and NES is about 15 km southwest of and outside the crater rim (Figures 1e and 1f). The NES landing site contains one of the most complete

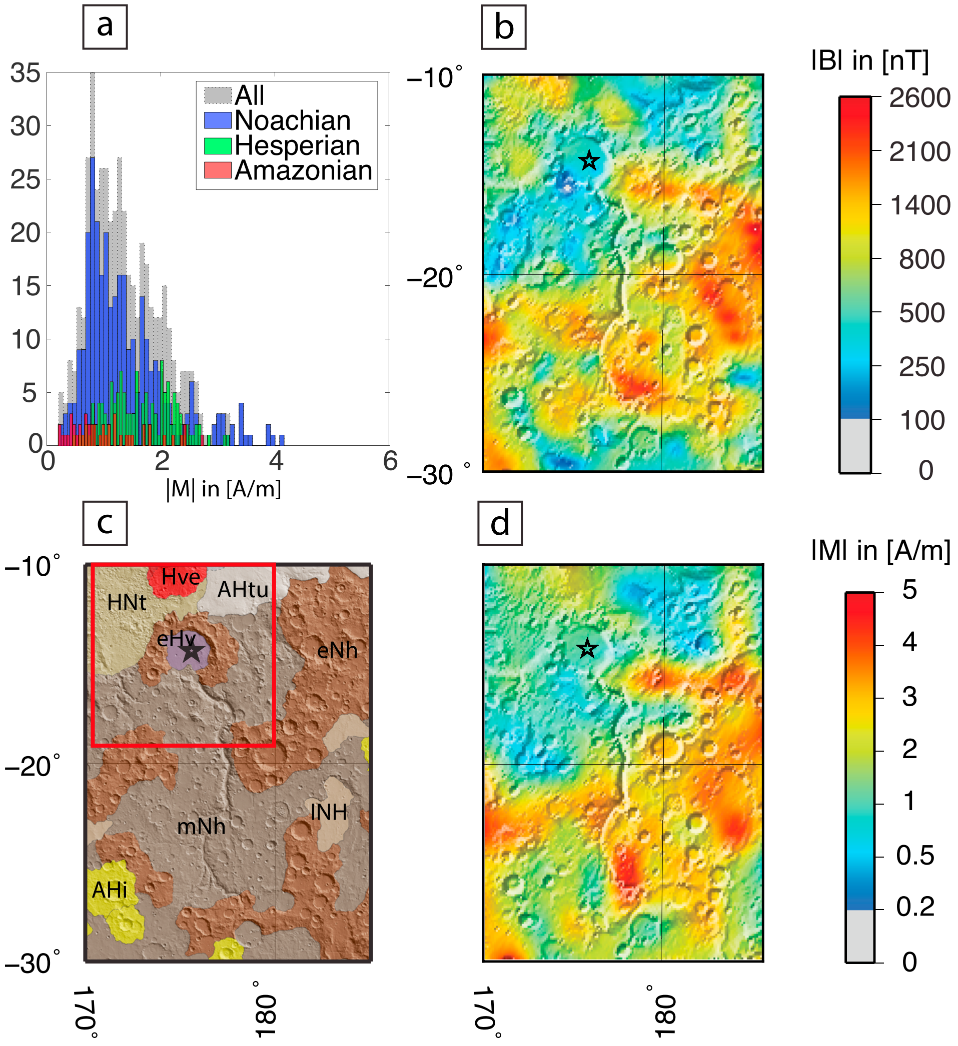

Figure 2. Gusev: (a) Histogram showing model magnetization distributions for each geological time period after Tanaka et al. (2014) where the investigated area (red square in c) spans ±5° of the approximate location of the landing site. (b) Model magnetic field magnitude, |B|, at the planetary surface. (c) Geologic map (Tanaka et al., 2014) AHi = Amazonian and Hesperian impact unit; AHtu = Amazonian Hesperian transition undivided unit; eHv = Early Hesperian volcanic unit; eNh = Early Noachian highland unit; Hve = Hesperian volcanic edifice unit; HNt = Hesperian Noachian transition unit; lNH = Late Noachian highland unit; mNH = Middle Noachian highland unit. (d) Model magnetization, |M|

sequences of ancient (pre-Noachian to Early Hesperian) igneous and possibly also sedimentary rocks on Mars. A phyllosilicate-rich igneous basement unit is overlain by olivine-carbonate rocks and a mafic capping unit (Bramble et al., 2017). An extended Mars 2020 mission might also access sulfate-rich rocks and Hesperian lavas. JE crater contains clastic sediments deposited as part of a fluvio-deltaic-lacustrine system during the Late Noachian to Early Hesperian, possibly covered in some locations by younger igneous rocks. The sediments are sourced from pre-Noachian to Early Hesperian NES regional rocks, similar to those exposed at the NES landing site. An extended mission outside the crater might be able to access these ancient rocks directly. Hence, sampling deltaic and lacustrine sediments of a paleolake is possible. Smectites and carbonate-bearing basin fill may be the result of aqueous alteration of olivine-rich material. Younger volcanic areas (Early Amazonian) complement the variety of possible samples reachable from the JE landing site (Ehlmann & Mustard, 2012; Hiesinger & Head, 2004). Outside the crater and closer to NES, olivine-carbonate rocks have been observed that are serpentinized and indicative of aqueous alteration. Thus, samples from acid sulfate formations, layered phyllosilicates, and volcanic and plutonic material are possible.

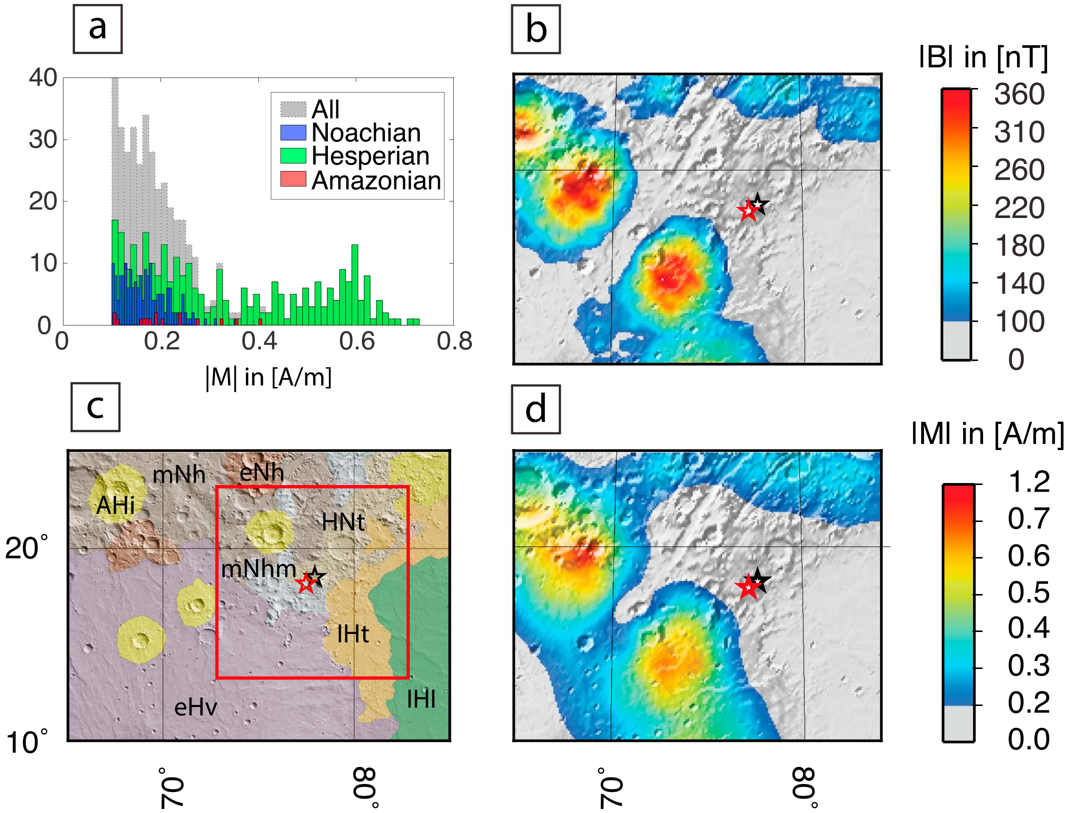

Figure 3. Jezero (black star) and NE Syrtis (red star): (a) Histogram showing model magnetization distributions for each geological time period after Tanaka et al. (2014), where the investigated area (red square in c) spans ±5° of the approximate location of the landing site. (b) Model magnetic field magnitude, |B|, at the planetary surface. (c) Geologic map (Tanaka et al., 2014). AHi = Amazonian and Hesperian impact unit; eHv = Early Hesperian volcanic unit; eNh = Early Noachian highland unit; HNt = Hesperian Noachian transition unit; lHl = Late Hesperian lowland unit; lHt = Late Heperian transition unit; mNH = Middle Noachian highland unit; mNhm = Middle Noachian highland massif unit. (d) Model magnetization, |M|

3. Magnetization Models

3.1. Methodology

Several magnetic field and magnetization models have been developed using MAVEN and MGS data and allow representations of magnetization and the magnetic field at different altitudes down to the planetary surface (e.g., Arkani-Hamed, 2004; Cain, 2003; Langlais et al., 2004, 2017; Mittelholz et al., 2017; Morschhauser et al., 2014; Purucker et al., 2000). Independent of the modeling approach, a major challenge is the nonuniqueness of such inversions and the resulting suites of possible models that can explain the observations equally well. A way of dealing with this is to assume a priori information. One such approach is to impose constraints on the geometry of the magnetized structure (e.g., Hood & Zakharian, 2001; Takahashi et al., 2014). Another involves solving the inverse problem for the minimum magnetization required to explain the magnetic field observations (Parker, 2003; Whaler & Langel, 1996; Whaler & Purucker, 2005). In this study we use two different approaches to model magnetization at the three landing sites using spacecraft data: a global and a regional approach.

Our global approach to estimate magnetization follows the work of Vervelidou, Lesur, Morschhauser, et al. (2017). In this approach, the magnetization was constrained by decomposing it into three parts, each being the projection on one of the three vector spherical harmonic (SH) basis functions as proposed by Gubbins et al. (2011). Of these, only one gives rise to the observable magnetic field; the other two span the null space of the inversion. Inverting a given SH magnetic field model only for the former, called the visible magnetization, Vervelidou, Lesur, Morschhauser, et al. (2017) yielded a solution that fits the model perfectly and is unique for a magnetized layer of given thickness, over which the magnetization varies only laterally. Due to the uniqueness of the solution, the inverse problem reduces to a simple conversion formula between the SH coefficients of the

Table 1
Key Paleomagnetic Science Objectives for a Returned Mars Sample

Science Objectives	Site Requirements	NES	CH	JE
1. Determine the intensity of the Martian dynamo.	Samples old enough (pre-Noachian and Early Noachian) to have likely been magnetized in ancient dynamo magnetic field.	***	**	**
2. Characterize the dynamo reversal frequency and conduct magnetostratigraphy.	Samples should span a dateable large time interval, ~>1 Ma, during Early Noachian; orientation should be known to within 30°.	***	**	**
3. Constrain the effects of (i) heating and (ii) aqueous alteration on the samples.	Variety of samples: (i) heated samples and (ii) evidence of water at the surface.	**	***	**
4. Test the hypotheses that Mars experienced plate tectonics and/or true polar wander and constrain the tectonic and deformational history of the landing site.	Parent rock of sample should be in-place bedrock or at least contain paleohorizontal indicators such as bedding planes or stratified grain size sorting.	***	**	*
5. Determine the major mineral carriers of Martian crustal magnetization.	Site should offer a variety of mineralogies.	**	***	**
6. Constrain sediment sourcing, fluid flow, and the depositional environment using environmental magnetism studies.	Site should offer environments where evidence for sediment deposition and fluid flow exists.	**	***	**

Note. Key paleomagnetic science objectives for a returned Mars sample adapted from Weiss et al. (2018) with their respective requirements and a rating of landing sites, where three asterisks mean the highest chance and one asterisk means the lowest chance to fulfill requirements for Northeast Syrtis (NES), Columbia Hills (CH), and Jezero (JE).

magnetic field and the vector SH coefficients of the visible magnetization. Based on this method, Vervelidou, Lesur, Morschhauser, et al. (2017) derived a visible magnetization model of Mars, assuming a magnetized layer of 40 km and using the SH model of Morschhauser et al. (2014), derived from MGS data. The magnetization intensity is shown in Figure 1b.

We also solve for the magnetization (Figures 2d and 3d) required to explain magnetic field observations using equivalent source dipoles as introduced by Mayhew (1979). The observed measurements at any point can be described by the sum of the fields due to regularly spaced dipoles (here every 115 km) placed within a constant thickness layer (here 40 km). The input data set is generated by subselecting MGS and quiet MAVEN data, as described in Mittelholz et al. (2018). For a set of possible model solutions, we examine the L-curve to find a reasonable trade-off between model complexity and misfit (Aster et al., 2011) and use the resulting model to predict the surface field (Figures 2b and 3b). Here we show regional models of the magnetization and the magnetic field predicted at the surface around the landing sites (Figures 2b, 2d and 3b, 3d).

3.2. Global Context

Measured from orbit, the strong crustal magnetic fields are mostly confined to the southern hemisphere, where they exceed the Earth's lithospheric field strength by an order of magnitude, and show substantially weaker but nonetheless significant signatures in the north. Magnetization as shown in Figure 1b is broadly correlated with topographically higher and on average older areas (Figure 1a; Tanaka et al., 2014). Both exogenic (impact-related differences in crustal structure) and endogenic (hemispheric dynamo and/or internally driven differences in the distributions of magnetic carriers) processes have been invoked to account for the north-south magnetic dichotomy (Amit et al., 2011; Andrews-Hanna et al., 2008; Marinova et al., 2008; Monteux et al., 2015; Quesnel et al., 2009; Stanley et al., 2008; Watters et al., 2007). The JE and NES landing sites are located west of Isidis, the youngest of the large (>1,000 km) unmagnetized impact basins. The lack of magnetization suggests that the JE impact occurred after the shutdown of the global dynamo and either impacted partially demagnetized crust or resulted in demagnetization without new acquisition of magnetization. CH is located in an area of appreciable magnetization north of the strongest magnetic fields on Mars.

3.3. Regional Models

A more detailed picture of the magnetic environment of the candidate sites, derived from regional magnetization models, is shown in Figures 2 and 3. The predicted magnetic field at the surface of the CH landing site reaches around 400 nT with a magnetization of 1 A/m, under the assumption of a 40-km magnetized layer. The mean values across the entire modeled region are 900 nT and 2 A/m. Predicted model magnetization and surface fields at the JE and NES landing sites are around 0.1 A/m and 35 nT, respectively, with mean values of 0.2 A/m and 100 nT across the entire modeled area in Figure 3. Values below 0.2 A/m and 100 nT (shaded gray in Figures 2b, 2d, 3b, and 3d) may however be considered below noise levels and are thus consistent with no magnetization and no magnetic field, respectively. However, localized fields could be much stronger, as only wavelengths of around 130 km can be resolved by currently available satellite data from Mars.

4. Paleomagnetic Science Objectives and Candidate Landing Site Assessment

A community-based study (Weiss et al., 2018) developed a ranked list of science objectives (column 1 in Table 1) for paleomagnetic studies with returned samples. In the following, we discuss each of these science objectives, and the resulting site requirements (column 2), and evaluate the potential of the proposed Mars 2020 landing sites to address these (column 3).

4.1. SO1 — Paleodynamo Intensity

4.1.1. Science Objective

The paleointensity of the Martian core dynamo field can be constrained if the magnetization and ferromagnetic mineral content of the crust is known. Such information cannot be recovered from satellite data because of nonuniqueness (Gubbins et al., 2011; Runcorn, 1975) and because the magnetic mineral content of the deeper crust cannot be inferred from orbital spectroscopic measurements. Therefore, the only direct constraint on the intensity of the Martian dynamo magnetic field is based on the meteorite ALH 84001, which contains 4.1-Ga-old thermoremanence and suggests a paleofield within the same order of magnitude as the present Earth main field, i.e. ~50 μT (Gattacceca & Rochette, 2004; Weiss et al., 2008). However, the inferred magnetization is too weak to explain the locally strong magnetic field anomalies associated with some of the old Noachian terrains. The meteorite has a complex postformational history with multiple thermal and deformational events (including ejection from Mars) that may have altered its original magnetization (Weiss et al., 2008). The need for samples magnetized during an active core dynamo is therefore the first paleomagnetic science objective for Mars.

This objective requires a site where material magnetized by a paleodynamo field is easily accessible. Based on inferences regarding the dynamo history from satellite data, this implies that a candidate site should include pre-Noachian and Early Noachian terrain.

4.1.2. Site Evaluation

To address SO1, we first evaluate the magnetization strength in the regions around the candidate landing sites CH (red square in Figure 2c) and JE/NES (red square in Figure 3c), by assigning each 0.5° × 0.5° region (~900 km^2) its mean magnetization value and the dominant stratigraphic period. At this scale, the strongest and most spatially extensive magnetic anomalies are associated with Noachian terrain at CH (Figure 2a), whereas most of the predicted magnetization for JE and NES is very weak, below 0.6 A/m, and is associated with Hesperian terrain. From this analysis, the likelihood of picking up a magnetized rock of Noachian age appears to be low at the JE and NES landing sites. However, given that the rocks exposed at the JE and CH landing sites are thought to be no older than Late Noachian, they are unlikely to provide bulk rocks that are magnetized if the dynamo was active only during the pre-Noachian to Early Noachian. In contrast, the megabreccia basement at NES, thought to have been produced by the Isidis impact, and therefore Middle to pre-Noachian in age (Fassett & Head, 2011; Frey, 2008; Werner, 2008) is a high-priority target for paleomagnetic studies. Megabreccia, a cataclastic deposit of large (≥10-m diameter) blocks within a finer-grained matrix, may represent the oldest exposed and accessible material. If layered, they provide a window into intact stratigraphy of ancient crust (Weiss et al., 2018). For the JE landing site, although the rocks are young, some mineral grains and clasts in the sediments could be as old as pre-Noachian because they are derived from the JE watershed that includes megabreccia. An extended mission could actually access the old JE watershed rocks directly. Gusev crater is the catchment area of Ma’adim Vallis, which is carved in Early and Middle Noachian material and could also contain material from those units. Furthermore, the magnetic field at NES and JE may be weak because the Isidis impact disrupted the magnetized crust, thereby removing its spatial coherence and consequently its magnetic signature at orbital altitudes. Substantial local exposures could still be magnetized while not visible magnetically at orbital altitudes. Hydrocode simulations formerly used for the Orientale Basin on the Moon (Johnson et al., 2016) suggest that megabreccia deposits have not been completely demagnetized by the impact. In contrast, Late Noachian and younger magnetized material could be a result of an older underlying magnetized layer, i.e. magnetization due to crustal rather than dynamo fields.

SO1 can therefore best be addressed by sampling layered megabreccia at NES. JE and CH are alternative second choices, because of weak magnetization and possible lack of ancient material, respectively.

4.2. SO2 — Paleodynamo Reversals and Magnetostratigraphy

4.2.1. Science Objective

Paleodirection of the ancient field is also of interest. It is known that the terrestrial core dynamo reverses its polarity about every $10^5 - 10^6$ years (Cox et al., 1964; Merrill & McElhinny, 1983), with intermittent longer periods of stability. Such reversals likely also occurred on Mars, based on our current understanding of dynamo theory and satellite magnetic field data (Connerney et al., 1999; Thomas et al., 2018). However, in most cases it is not possible to associate an age with a given pole orientation, as most crustal anomalies cannot be clearly associated with a dateable surface expression, such as a volcano or impact crater, and more generally because the surface age may not reflect the timing of subsurface magnetization acquisition. On Earth, field reversals are identified from paleomagnetic directions in samples with known georeferenced orientation (Butler, 1992). A definite identification of a reversed polarity would be the first direct evidence for field reversals on Mars or on any other planet besides Earth. Paleomagnetic samples from Mars would provide the first direct measurements of paleofield direction, hopefully with a known absolute age obtained from radiogenic dating. They might eventually even offer the possibility to establish a partial chronology of field reversals for Mars, if enough samples of different ages are available. The frequency of reversals is an important constraint on the dynamics of the core (Driscoll & Olson, 2009; Ryan & Sarson, 2007) and convective regime of the mantle (Olson et al., 2013; Pétrélis et al., 2011). Polarity changes have also been hypothesized to lead to weaker magnetization for prolonged cooling rates and could be an explanation for a lack of magnetization in some Noachian-aged areas (Rochette, 2006).

The identification of distinct magnetic polarity has modest requirements on the precision of paleodirection, that is, knowing the direction to about 30° would be sufficient. The investigation of magnetostratigraphy requires analysis of multiple samples covering the time frame over which the dynamo was active and for a long enough duration to capture reversals. In this respect, the site age requirements of S01 apply to S02, but in addition reconstruction of the original orientation and sample context are required. The paleomagnetic measurements should be coupled with radiometric dating of the samples.

4.2.2. Site Evaluation

To achieve SO2, we need rocks magnetized in a dynamo field where reorientation, by, for example, impacts or tectonics, of the blocks has not occurred, is negligible or traceable. The basement rocks of JE and NES are located close to the demagnetized Isidis basin and may have been reoriented during the impact. Megabreccia in NES represent outcrops spanning an extended contiguous time frame. Some megabreccia exposures near, but not in, the landing site are layered (Weiss et al., 2018), and because different blocks are derived from similar locations in the original bedrock, they possibly provide access up to hundreds of meters of intact stratigraphy. Following the argument in SO1, we argue that megabreccia and therefore NES is the preferred sampling site for SO2. An extended mission would allow access to megabreccia from JE. However, the location close to the Isidis basin could be a disadvantage for NES and JE.

4.3. SO3 — Heating, Alteration, and Radiolysis

4.3.1. Science Objective

Because the interest in paleomagnetic samples is mostly focused on ancient samples, thermal or chemical alteration is a key issue in sample selection and analysis. Although the main Mars 2020 mission goals address biosignatures and habitability, alteration or preservation state of the sample also has implications for the magnetic field record. An original magnetization can be altered, overprinted, or entirely erased by subsequent thermoremanent magnetization (TRM) or chemical remanent magnetization (Butler, 1992). Therefore, samples that were unaltered following magnetization acquisition in a core dynamo field are preferred. Vice versa, the acquisition history of TRM in a Martian rock sample may be revealed in the laboratory and the original magnetization and subsequent overprints identified. Rock magnetic studies, together with petrological studies of composition and fabric could identify, for example, magnetic minerals formed during serpentinization, as well as signatures of metamorphism. Collectively, these studies will better inform the roles of aqueous alteration and metamorphism in the magnetization record of the Martian crust (Gunnlaugsson et al., 2006; Harrison & Grimm, 2002; Quesnel et al., 2009) aiding the interpretation of satellite data and better constraining the timing of the core dynamo (Langlais & Purucker, 2007; Lillis et al., 2006).

Different geologic units are more prone to different alteration processes. For example, thermal alteration of paleomagnetic samples is most likely for volcanic units, and chemical alteration involving water may be found in deltaic sediments. Ideally, we are interested in magnetized samples of a variety of host rocks.

4.3.2. Site Evaluation

All three candidate landing sites offer a variety of possibilities for collecting samples from different units, and drills and abrasion tools will help obtain samples minimally affected by surface alteration. Because the origin of the magnetization is not important for SO3, preference would be given to CH, as we expect more widespread magnetization of samples from a variety of sources, for example, volcanic Ma'adim watershed, etc. NES would offer megabreccia but possibly not a broad range of magnetized samples, and magnetized samples around JE could generally be very limited.

4.4. SO4—Plate Tectonics and True Polar Wander

4.4.1. Science Objective

On Earth, estimates of paleopole locations from paleodirections allow to investigate paleosecular variation, changes in the planet's rotation axis (true polar wander), or movement of tectonic plates (apparent polar wander). Paleopole locations are used to reconstruct plate motions (e.g., Metelkin et al., 2010; Weil et al., 1998); however, it is unknown if plate tectonics operated on early Mars (Connerney et al., 2005; Fairén et al., 2002; McKenzie, 1999; Sleep, 1994; Sprenke & Baker, 2000). Also, knowing the magnetization direction at one location may help to further constrain the behavior of the paleodynamo. On Earth, the geocentric axial dipole hypothesis is commonly used to relate location latitude and direction (inclination) of the paleofield. Although we acknowledge that samples from one specific location on Mars would not suffice to distinguish among paleosecular variation, true and apparent polar wander, studying paleopoles on Mars, their current location with respect to the rotation axis, and putting this in a global context will also shed light on the dynamo processes. Addressing this objective will thus help tackle some of the most fundamental questions related to Martian history.

Paleopole locations for Mars have been estimated from satellite magnetic field data by analyzing mostly isolated crustal anomalies (e.g., Hood & Zakharian, 2001; Langlais & Purucker, 2007; Milbury et al., 2012; Thomas et al., 2018). However, large uncertainties are associated with inferring paleopole positions from satellite data (Thomas et al., 2018; Vervelidou, Lesur, Morschhauser, et al., 2017). Paleomagnetic samples from Mars, with known orientation, will help in narrowing down these uncertainties. Similar to SO2, in order to estimate paleodirections from a sample, the geologic context has to provide in-place bedrock or paleohorizontal indicators, but with higher accuracy as for SO2. The paleolatitude of the pole could then possibly be inferred. This objective requires careful diagnosis of outcrops with camera images, where outcrops must contain paleohorizontal indicators, such as bedding planes, flow top features, vesicularity or crystal size gradients, and/or stratified grain size sorting (Weiss et al., 2015).

4.4.2. Site Evaluation

Following the arguments regarding magnetization and timing in SO1 and orientation in SO2, NES is the preferred site, followed by CH and JE.

4.5. SO5—Magnetic Carriers

4.5.1. Science Objective

Many studies have addressed the question of what mineral carriers could produce the observed strong Martian crustal magnetic fields (e.g., Arkani-Hamed, 2005; Dunlop & Arkani-Hamed, 2005; Kletetschka et al., 2000). The most discussed candidates are single-domain (SD) and multidomain (MD) magnetite, MD hematite, pyrrhotite, or ilmenite lamellae. Of these, SD magnetite can acquire strong TRM, and its relatively high Curie temperature of 580° C allows for up to 40–50 km of magnetized crust given the present Martian geotherm. Additionally, it has been argued that fine-grained SD magnetite could preserve its remanence over 4 Gyr (Sato et al., 2018).

There are a number of magnetically interesting Martian meteorites whose magnetic properties have been described and are dominated by magnetite: SD-sized magnetite has been discovered in the Amazonian-aged nakhlites and shergottites (e.g., Cisowski, 1986, Funaki et al., 2009, Jambon et al., 2016, Herd et al., 2017). However, the magnetic properties of these younger rocks may differ from those of older, more strongly magnetized crust. SD magnetite is difficult to form during slow intrusive cooling events (Butler, 1992), and many alternative formation processes (e.g., Quesnel et al., 2009, Gunnlaugsson et al., 2006, Scott & Fuller, 2004) have been suggested. MD hematite is another good candidate, mainly due to its efficient TRM (Dunlop & Kletetschka, 2001; Kletetschka et al., 2000), and it has been detected in nakhlites (McCubbin et al., 2009) and NWA 7034 (Wittmann et al., 2015). In contrast, shergottite meteorites show that pyrrhotite is generally the main magnetic carrier, and for nakhlites it is titanomagnetite (Rochette et al., 2001). Although pyrrhotite can hold a strong TRM, its Curie temperature is only 320° C (Dunlop & Arkani-Hamed, 2005), thus limiting the depth of the magnetized layer to ∼20 km, and it can also easily be demagnetized by impact shock (Rochette et al., 2003). NWA 7034 is dominated by magnetite and contains maghemite that could explain the observed strong crustal fields on Mars, and hydrothermal alteration may have led to its mineralogy (Gattacceca et al., 2014). The oldest Martian meteorite, ALH 84001, contains SD magnetite (Antretter et al., 2003; Weiss et al., 2002) and pyrrhotite (Weiss et al., 2008).

Because of the overall basaltic composition of most Martian crustal rocks (McLennan & Grotzinger, 2008), reflecting the scarcity of clastic felsic sediments and chemical weathering, ferromagnetic minerals are abundant on the surface (McSween et al., 2009). This is true even for Martian sediments like sandstones and claystones, which are far more enriched in ferromagnetic minerals than their typical counterparts on Earth. For example, magnetite, hematite, and pyrrhotite are each present at 1–5 wt.% levels in mudstones and aeolian deposits in Gale crater (Vaniman et al., 2013), and hematite is present at 10 wt.% in the sulfate-rich outcrops of Meridiani Planum (Christensen et al., 2004). Pyrrhotite has also been found at Gale crater (Vaniman et al., 2013). Even Martian airborne dust is highly magnetic (∼0.3–0.5 wt.% magnetite; Goetz et al. 2008). These pyrrhotite and magnetite abundances are broadly similar to those of Martian meteorites. Ilmenite lamellae have also been suggested as a candidate mineralogy with properties allowing for high NRM and coercivity and requiring a layer as thin as ∼10 km to explain the observed strong magnetic anomalies (McEnroe et al., 2004).

There are still many open questions regarding magnetic carriers on Mars. In particular, it is not sufficiently understood how the observed strong magnetization of Mars may be explained given the most common ferrimagnetic or ferromagnetic minerals and a magnetizing field strength similar to Earth's core dynamo (Morschhauser et al., 2018). Furthermore, knowing the magnetic mineralogy would allow understanding of how impacts, volcanic eruptions, and viscous decay influence NRM. These would, in turn, better constrain the core dynamo timing and magnetization depths. Finally, the nature and abundances of ferromagnetic minerals may place fundamental constraints on how the crust has been aqueously altered (Scott & Fuller, 2004), which has major implications for habitability (Grotzinger et al., 2014). Returned samples from Mars could greatly help answering these questions, in particular if they are selected from igneous rocks that crystallized in the deeper crust.

4.5.2. Site Evaluation

The investigation of magnetic carriers does not necessarily require magnetized rock but minerals that could carry magnetization when exposed to a magnetic field. A variety of different samples would offer a chance to explore a variety of mineralogies. We give a slight preference to CH, as we do know that rocks carry magnetization and we will therefore find possible carriers. However, the JE and NES landing sites are located closely to the Syrtis volcanic plains and may therefore also be suitable landing sites in this respect.

4.6. SO6—Sediment Sourcing and Fluid Flow

4.6.1. Science Objective

Detrital remanent magnetization is a further mechanism to magnetize rocks. The sample acquires magnetization by alignment with the ambient field during or past deposition. Fluid flow can lead to alignment of ferromagnetic particles when they are exposed to a magnetic field (Butler, 1992). Vice versa, if such magnetic anisotropy was detected, we can inversely infer paleo fluid flow direction. Also, alteration of ferromagnetic minerals (such as hematite or maghemite) would suggest extensive exposure to liquid water, whereas less oxidized magnetic minerals (magnetite) would suggest transient water. Requirements for a landing site should include signs of fluid flow ideally during an active global dynamo field or in regions of strong crustal magnetization.

4.6.2. Site Evaluation

SO6 follows the same argument as SO5, where all sites fulfill the morphological requirement of fluid flow at the surface, but CH also carries magnetization.

5. Discussion: Paleomagnetic Considerations for Mars 2020 Final Site Selection

From a satellite data perspective, the obvious first choice for a landing site would be CH, since it is the only site with considerable magnetization as seen from orbit. However, SO1, SO2, and SO4 require sampled material to be magnetized by a dynamo field, and the best likelihood of this is if the samples are pre-Noachian or Early Noachian. Material around CH is believed to be Late Noachian and younger. A sample from this site therefore has a chance of not addressing the science objectives related to an ancient paleodynamo field. Magnetization inferred from orbital data might also reflect magnetized material underlying the surface volcanic unit. Lava cooling in the magnetized crater could then still carry an NRM (even in absence of a dynamo field) but one that was acquired in presence of nearby crustal fields resulting from the magnetized basement units. This would allow objectives that do not require Early Noachian material, for example, SO3, SO5, and SO6, to still be addressed. Furthermore, if, as suggested by some studies (Langlais & Purucker, 2007; Milbury et al., 2012; Schubert et al., 2000), the dynamo extended into and beyond the Late Noachian, material from CH would allow S01 and, depending on geological context, possibly S02 to be addressed.

Megabreccia blocks have been observed in central peaks and rims of Noachian impact basins; specifically eight have been mapped within the NES landing site (and JE for an extended mission), which make this site an attractive choice (Weiss et al., 2018). Because many megabreccia blocks are layered and adjacent blocks often originate from similar original bedrock locations, they might provide access to hundreds of meters of ancient crust (Weiss et al., 2018). The chance of sampling pre-Noachian and Noachian material as well as intact stratigraphy would address SO1, SO2, and SO4. However, the best exposures of megabreccia deposits are currently outside the suggested NES landing ellipse and a slight change in landing location was proposed to accommodate access to them (Weiss et al., 2018). We note that the absence of regional magnetization inferred from orbital measurements is still compatible with the presence of strong localized magnetizations. By analogy, lunar surface magnetic fields in the vicinity of the Apollo 12 landing site, inferred from orbital data, are very weak, but specific samples from this landing site have shown evidence for magnetizations acquired in a dynamo field (e.g., Cournède et al., 2012).

Selection of magnetized samples would be greatly aided by having a magnetometer as part of the scientific instrument payload. This would allow outcrops to be surveyed prior to sampling, as well as permit a ground-based survey of the crustal magnetic signature (Diáz-Michelena et al., 2016).

The overall location of NES and JE might be a disadvantage because they are adjacent to the large impact basin Isidis. The 1,352-km-diameter basin is dated at 3.85 – 4.06 Ga (Frey, 2008), and the absence of magnetization within the basin has been interpreted as a demagnetization signal. Impacts can also result in stratigraphically inverted sections, with no easy way to identify the inversion. This could negatively impact achieving objective SO4. Shock and thermal alteration of nearby rocks may be an issue, and evaluation of these effects will be important for SO1, SO3, and SO5. In contrast, Gusev crater in CH is of Early Noachian age, and so the crater basement acquired magnetization after the impact with no subsequent impact-related disturbance of possible samples.

In conclusion, NES provides access to megabreccia, the oldest known materials on Mars and the basement unit of NES likely also contains Early Noachian materials. Thus, this site is the top choice for paleomagnetic sampling. The other sites also offer promising opportunities: CH is a good choice, motivated by the strong crustal fields measured from orbit and the absence of a major postdynamo impact crater. It may not be possible to address questions related to an ancient (pre-4.1 Ga) dynamo field with samples from CH, but it should be possible to test whether a dynamo was present during the Late Noachian or Early Hesperian period. Furthermore, the mineral grains and clasts in sediments around CH could be as old as Early Noachian because they are likely derived from Ma'adim Valley. Similar possibilities exist at the JE landing site, where Late Noachian-Early Hesperian material is abundant, sediments could be derived from megabreccia in the JE watershed, and where an extended mission could access such watershed rocks directly.

6. Conclusion

Martian return samples will revolutionize understanding of our neighbor planet, including from a magnetics perspective. All of the remaining three candidate landing sites will provide unprecedented information about the history and record of the magnetic field, and we suggest that the preferred site is NES. Satellite observations indicate weak or no magnetic field signatures at NES and JE, and a moderate magnetic field signature at CH. However, to address the magnetic signature generated by the ancient dynamo field, samples of pre-Noachian and Early Noachian age are required, which is likely not the case for CH and JE, but is the case for NES. Specifically, the megabreccia deposits may provide samples, that represent earliest records of the Martian paleodynamo field and also provide insight into paleoclimate and habitability including aqueous processes, biosignatures, planetary accretion, and igneous differentiation (Weiss et al., 2018). A recommendation for Mars 2020 or future lander sample missions is the inclusion of a magnetometer to survey potential outcrops for magnetic field signatures ensuring the best possible target sample and increased science return for the overall mission.

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