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Martian Impact Fracturing Pervasively Influences Habitability

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Key Points:

- Impact have fractured the deep subsurface of Mars pervasively
- We estimate this fracture area to be between 9,200 times the surface area of a Mars radius sphere and up to 100 times this value
- This fracturing has likely profoundly influenced habitability

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract On Mars, the lack of either plate tectonics or a prominent erosional hydrological cycle since the Noachian means geological changes caused by asteroid and comet impact events have been preserved. On Earth, surviving impact-induced fractures are localized to the relatively few preserved craters on the planet. We estimate that the shell of impact-fractured rock on Mars (the "impact-sphere") could provide between 9,200 times the surface area of a Mars radius sphere and up to 100 times this value, depending on the assumptions made, as potential microbially accessible space. Although >93% of craters we consider are smaller than 10 km in diameter, they contribute only about 5% of the total fracture surface area generated by all craters, making complex craters the dominant process for potential habitat formation. Microbiological data from terrestrial impact craters suggest that these fractures could have significantly enhanced local habitability by providing pathways for fluid flow, and thus nutrients and energy. However, unlike on Earth, the geological history of Mars means that pervasive impact fractures may also have provided pathways for Hesperian and Amazonian brines to infiltrate the subsurface and locally reduce habitability. Combining the fracture data with previous microbiological observations provides testable hypotheses for Martian drilling missions.

Plain Language Summary The Martian surface and subsurface is pervasively fractured by asteroid and comet impacts, largely because, compared to Earth, they have not been subducted by plate tectonics or eroded by a vigorous water cycle. In this paper, we estimate the surface area of fractures generated by these impacts. We find that these impact fractures could be 9,200 times the equivalent surface area of a flat Mars-sized sphere and up to a hundred times this, depending on the assumptions made. On the one hand, these fractures could have provided surfaces for life and improved the flow of nutrients, on the other hand they could have channeled deleterious salty waters into the subsurface, suggesting that habitability of the subsurface is profoundly influenced by impact, but its positive or negative effects depend on the history of water flow and brine formation. This study leads to several testable hypotheses about the subsurface habitability of Mars.

1. Introduction

The study of the biological effects of asteroid and comet impacts has generally focused on their capacity to cause ecological destruction, particularly on the global scale. For example, an asteroid impact is implicated in the end-Cretaceous mass extinction (e.g., Abramov & Mojzsis, 2009; D'Hondt, 2005; Hull et al., 2020; Schulte et al., 2010). Less attention is given to the effect of impact events on the local geological conditions and the implications for microbial persistence and growth. One reason for this is that on Earth, asteroid and comet impact craters and their associated fracture zones are rare, most of them having been eroded by wind and the hydrological cycle, buried by accumulating sediment, or destroyed by plate tectonics. There are about 190 confirmed impact structures on Earth (Kenkmann, 2021; Osinski et al., 2022). By contrast, on Mars the lack of plate tectonics and the subdued hydrological cycle since the Hesperian have helped to preserve a record of substantial impact bombardment (Osinski et al., 2013). One database includes over 380,000 craters with a diameter of 1 km or greater (Robbins & Hynek, 2012).

Rodriguez et al. (2005) point out the important role of impact fracturing in shaping the geology of Mars and suggest that pervasive fracture networks, including radial and concentric fractures that can overlap between craters, have been pivotal in determining the hydrogeology of the planet. Using the eastern circum-Chryse region as an example, they show how subsidence and collapse features on Mars, including chaotic terrains, may be caused by weaknesses induced by extensive impact fracturing.

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It follows from the work of Rodriguez et al. (2005) that the effects of impact cratering on subsurface fracturing and aqueous fluid movement could have profoundly altered the habitability of the Martian crust.

Impact events are destructive to a biota, largely because of the transformation of the kinetic energy of the impactor into heat energy, mechanical movement of rock, blast wave production, and climatic effects, all of which can be highly deleterious to fragile organic molecules and structures (Kring, 1997; Schulte et al., 2010; Sleep et al., 1989). Yet, it is now known that once these initial extremes have subsided, impacts can leave a legacy of improved conditions for microbial life. For example, Cockell et al. (2002, 2005) and Pontefract et al. (2012, 2014, 2016) showed that impact-induced fracturing and porosity enhancement in crystalline rock (gneiss) improved its availability for microbial growth. Indeed, impact fractures in the near-surface can provide habitat space for a diversity of biota, including animal life (Cockell & Lee, 2002; Cockell et al., 2003). Similar enhancements in microbial growth have been observed associated with impact-induced fracturing and porosity elevations in the deep subsurface (Cockell et al., 2009, 2021). Impact-induced fracturing is likely to enhance microbial growth by providing improved pathways for fluid flow, and thus redox couples, nutrients and liquid water required for life. Impact-induced fracturing, when coupled to the thermal excursion caused by the impactor, is likely to lead to hydrothermal systems, which will provide microbial habitat space (Kirsimae & Osinski, 2012; Osinski et al., 2013). Similar improvements in microbial conditions have been postulated to be caused by tectonic activity-induced fracturing (Sleep & Zoback, 2007).

Given previous work showing that impacts should produce pervasive fracturing and pore space generation (Alexander et al., 2024; Wiggins et al., 2022), and recognizing the effects of impact fracturing on microbial habitability, in this study we sought to make a first-order estimate of the potential space available in the Martian subsurface created by the pervasive impact-fracture networks in order to arrive at quantifiable statements about the potentially habitable space. We focus on surface area generation, as this is a proxy for the attachable space for microbial communities (although microbes can grow planktonically in the fracture volume and the volume will influence fluid flow, etc). For want of an established term, we might describe this planetary-scale annulus of impact-fractured material as the "impact-sphere." The calculations are subject to considerable uncertainties, discussed here, that will ultimately only be resolved by gathering more geophysical data and/or deep drilling across Mars to obtain better information about its subsurface. The calculations we make on the biological consequences of impact fracturing motivate several testable hypotheses, which we discuss. The calculations are sufficient to illustrate the importance of impacts in shaping habitability on Mars.

2. Materials and Methods

The calculation of subsurface fracturing caused by impact, and the proportion of any unit volume being transformed into microbially accessible fracture space is highly complex and stymied by a lack of comprehensive data. For example, we lack fundamental data on the behavior of different Mars analog rocks (primarily basalt, but also sedimentary rocks derived from primary basalt) under impact shock, such as the Hugoniot relations of diverse Mars-like materials. Even with such theoretical data, the extent of fracturing will depend on local conditions, the presence of subsurface fluids, layering and any pre-existing weaknesses in the rock.

To arrive at an estimate of impact fracture space, we consider two independent calculations. The first is based on shock physics calculations of tensile fracturing and pore-space generation beneath large impact craters on the Moon and Mars. While this approach is entirely theoretical, and assumes idealized impact conditions and target properties, it offers important insights into the likely geometry, scale and fracture spacing of fracture zones around large craters. The second approach is based on the magnitude of the Bouguer gravity anomaly at terrestrial craters, which is a direct consequence of impact-generated fracturing and fragmentation. While this approach is compromised by the differences in gravity and target properties between Earth and Mars, its basis in physical measurements of density reduction provide a completely independent assessment of the degree and extent of fracturing beneath impact craters.

2.1. Fracture Area From Numerical Simulations of Tensile Fragmentation

Wiggins et al. (2019) simulated tensile fragmentation induced by impacts on the Moon, as well as an exemplar asteroid impact on Mars. Wiggins et al. (2022) extended this work to calculate pore space generation caused by tensile fracturing. These simulations showed that impacts produce an approximately hemispherical zone of tensile

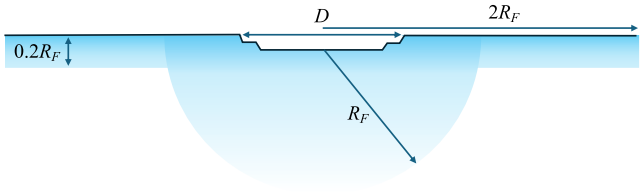


Figure 1. Schematic showing simple geometric model used in this paper.

fragmentation, as well as a much broader and shallower near-surface spallation zone. For a 1-km diameter asteroid impacting a dense basaltic crust with Mars' surface gravity at 15 km/s, the fragmentation hemisphere was approximately 16 km in radius. Wiggins et al. (2019, 2022) did not simulate crater formation, so we use complex impact crater scaling (Johnson et al., 2016) to estimate a crater size of 15 km for the impact they simulated that produced a fracture zone radius of 16 km. Predicted average fragment sizes showed little dependence on impactor size and were approximately 1 m in the fragmentation hemisphere and more than 10 times larger in the spallation zone. Porosity created by tensile fragmentation ranged from 0.01% to ~1% in the fragmentation hemisphere and spallation zone (Wiggins et al., 2022).

We use these observations to construct a simple geometric model for the total fracture area beneath a typical complex crater on Mars (Figure 1). The fracture volume has two zones: an inner hemispherical fragmentation zone of radius R_F and an outer near-surface fragmentation zone or halo with the geometry of a rectangular torus with inner and outer radius R_F and $2R_F$, respectively, and height $0.2R_F$. Later we will apply this model for a range of crater sizes by assuming $R_F = D$.

In this study, we do not include the surface area within the ejecta material or in impact melt generated locally or within ejecta. Our focus is on quantifying the effects of impact fracturing on the habitability of the deep subsurface. However, fractured ejecta deposited on the surface of Mars would provide additional habitat space and so too could impact melt, especially material that is eventually weathered, creating permeable interiors for microbial growth.

The total fracture area in either fragmentation zone simulated by Wiggins et al. (2019) is related to the peak of the fragment size distribution L and the volume of the fragmentation zone V_F:

$$A_F = \frac{3(m+3)}{m+2}\frac{1}{L}V_F = \frac{3.26}{L}V_F \tag{1}$$

where m is the exponent in the flaw activation distribution $N = k\epsilon^m$, assumed to be 9.5 by Wiggins et al. (2019). Thus, the total fracture area is given by:

$$A_F = \frac{6.83}{L_H}R_F^3 + \frac{6.14}{L_S}R_F^3, \tag{2}$$

where the first term represents the fragmentation area within the hemispherical fragmentation zone and the second term represents the fragmentation area within the spallation zone. Note that this expression neglects the volume of the crater, which we assume is small relative to the volume of the fracture zone. For the impact on Mars presented by Wiggins et al. (2019), where $L_H \approx 1$ m, $L_H \approx 10$ m and $R_F \approx 16$ km, the total fracture area is 3.0×10^{13} m^2, or about 20% of the surface area of a Mars-radius sphere. We note that at this crater size most of the fracture area resides within the hemispherical zone owing to the 10 times smaller fragment size in this zone.

This estimate of fracture area assumes a uniform fragment size and fracture density over the entire fragmentation hemisphere. However, over time overburden pressure will reduce the pore space at depth, narrowing the fracture width and potentially closing the fracture area to the point it is rendered uninhabitable. In addition, Wiggins et al. (2019, 2022) showed that as crater size increases, overburden pressure also acts to suppress tensile fragmentation at depth within the fragmentation hemisphere. To correct our estimates of fracture area to account for both of these processes we apply a simple model of pore closure with depth.

The relationship between porosity and depth caused by lithostatic pressure on Mars is not empirically known, but can be estimated from the equation (Athy, 1930; Clifford, 1993):

$$\phi(z) = \phi_0 \exp\left(-\frac{z}{k}\right), \tag{3}$$

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where ϕ_0 is the porosity at the surface, z is the depth, k is the porosity e-folding depth. The average value of k for the lunar highlands is 9 km (Besserer et al., 2014). To adapt this to the martian case we scale the decay constant by the relative gravitational accelerations on the Moon and Mars, $k_{\text{mars}} = k_{\text{moon}}\ (g_{\text{moon}}/g_{\text{mars}})$, using the values $g_{\text{moon}} = 1.62\ \text{ms}^{-2}$ and $g_{\text{mars}} = 3.71\ \text{ms}^{-2}$ to obtain a value of $k_{\text{mars}} = 3.93$ km.

For simplicity, we assume a constant initial porosity ϕ_0 within the fragmentation hemisphere and spallation zone, which is then reduced by lithostatic pressure according to Equation 3. The total pore volume in the hemispherical fragmentation zone after pore closure can then be found by integrating Equation 3 over the hemisphere:

$$V_p = \pi\phi_0\left[2\left(R_F k^2 + k^3\right)e^{-\frac{R_F}{k}} + kR_F^2 - 2k^3\right], \tag{4}$$

And the fraction of the fragmentation hemisphere with open pore space and hence habitable fracture area is given by:

$$f_{\text{open}} = \frac{V_p}{\frac{2}{3}\pi\phi_0 R_F^3}. \tag{5}$$

A similar expression can be derived for the fraction of open pore space in the spallation zone, which leads to the following equation for the total open fracture area in both zones:

$$A_F = \frac{6.83}{L_H}\left[3\left(R_F k^2 + k^3\right)e^{-\frac{R_F}{k}} + \frac{3}{2}kR_F^2 - 3k^3\right] + \frac{6.14}{L_S}\left[1 - e^{-\frac{R_F}{5k}}\right]kR_F^2. \tag{6}$$

For the example scenario of a 15-km diameter crater, we take $L_H = 1$, $L_S = 10$, $k = 3.93$ km, and $R_F = 16$ km, which gives an open fracture area of 0.96×10^{13} m^2, or about 7% of the surface area of a Mars-radius sphere. In this case, overburden pressure has reduced the total fracture area by a factor of three.

2.2. Fracture Area From Gravity Anomalies of Craters on Earth

A completely independent estimate of open fracture area generated by a 15-km diameter crater can be derived from geophysical observations of terrestrial craters. The Bouguer gravity anomaly of almost all craters on Earth is negative, implying a mass deficit beneath the crater caused by fracturing. To a rough approximation the negative Bouguer gravity anomaly amplitude (in mgals) is equal to the crater diameter (in km) for craters up to about 30-km in diameter and then remains constant for larger craters (Pilkington & Grieve, 1992). In SI units, this may be expressed as:

$$\Delta g_0 = \min\left(10^{-8}D, 3 \times 10^{-4}\right), \tag{7}$$

where Δg_0 is the gravity anomaly amplitude in m s^{-2} (1 mgal = 10^{-5} m s^{-2}) and D is the crater diameter in m. The mass deficit ΔM responsible for this anomaly can be determined from the anomaly amplitude and extent by assuming a simple axially symmetric anomaly geometry $\Delta g(r)$. Here, we assume that the gravity anomaly has a parabolic profile:

$$\Delta M = \frac{1}{2\pi G}\int_0^R 2\pi r\Delta g(r)\,dr = \frac{\Delta g_0}{G}\int_0^R r\left(1 - \frac{r^2}{R^2}\right)dr = \frac{\Delta g_0 R^2}{4G}, \tag{8}$$

where G is the gravitational constant and R is the radial extent of the gravity anomaly. Assuming that the mass deficit is caused by fracture network pore space within a hemispherical fracture zone surrounding the crater, also of radius R, the average porosity ϕ in the fracture zone is given by the ratio of the mass deficit to the mass of rock in the fracture zone:

$$\phi = \frac{\Delta M}{M_F} = \frac{3\Delta g_0}{2\rho\pi GR}. \tag{9}$$

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For a 15-km diameter ($\Delta g_0 = -15$ mgal) crater on Earth formed in rocks with a density of 2,600 kg/m^3, this gives an average impact-induced porosity of 5.5% if we assume a gravity anomaly radius R equivalent to the crater radius. This is consistent with porosity measurements of rocks beneath several terrestrial impact structures (Collins, 2014; Innes, 1961; Masaitis & Pevzner, 1999).

To convert this into a fracture area we assume that this porosity is comprised of n planar fractures per unit volume with a fracture width of t; thus, $\phi = nt$ or $n = \phi/t$. In this case, the fracture area in the hemispherical fracture volume V_F is given by:

$$A_F = \frac{\phi}{t} V_F = \frac{2\pi\phi}{3t} R^3. \tag{10}$$

Taking a nominal fracture width of 0.1 mm, this implies a total fracture area of 4.85×10^{14} m^2 or approximately three times the surface area of a flat Mars-sized sphere.

2.3. Scaling Fracture Area With Crater Size

The two independent estimates described above of total fracture area associated with a single 15-km diameter crater are both comparable to the surface area of Mars and can be made to agree to within about an order of magnitude under plausible assumptions of fragment size and fracture width (discussed below). A sanity check of these estimates can be made by comparing the total energy required to create this fracture area to the impact energy ($\approx 7 \times 10^{19}$ J). Zhang and Ouchterlony (2022) determined a specific fracture energy (defined as the amount of energy necessary to create one unit area of a crack) for Dresser basalt of 25 J/m^2. Adopting this nominal value would imply a total energy for fragmentation of 2.4×10^{14}–1.2×10^{16} J, which is several orders of magnitude smaller than the impact energy and would thus require a fragmentation efficiency of only 10^{-4}–10^{-6}.

The estimate based on numerical simulations of tensile fragmentation is likely an underestimate as it does not account for shear-induced fracturing (Collins, 2014). It is also inversely proportional to the average fragment size, which can vary across the fragmentation zone and with target and impactor parameters (Wiggins et al., 2019). An average fragment size 10 times smaller (or larger) than the nominal 1 m adopted here would increase (or decrease) the total fracture area by the same factor.

The estimate based on gravity anomalies at terrestrial craters, on the other hand, carries several sources of uncertainty. Equation 7 is based on a relatively small sample size of 58 terrestrial craters (formation ages ranging from 50 ka to 2 Ga) with measured gravity signatures and the negative anomaly magnitudes exhibit considerable scatter. There is also uncertainty associated with the diameters of the craters used to compile Equation 7 owing to erosion (Turtle et al., 2005). The maximum negative gravity anomaly amplitude as a function of crater diameter is several times higher than the nominal anomaly amplitude assumed here (Pilkington & Grieve, 1992), and while several post-impact processes might act to reduce porosity, such as occlusion of pores by secondary minerals or gravitation settling, it is hard to envision a post-impact process that would act to increase subsurface porosity. Thus, the estimate based on gravity anomalies may also underestimate the total fracture area. This estimate is also inversely proportional to the assumed characteristic fracture width and could be 10 times larger if we assumed a fracture width of 0.01 mm as opposed to 0.1 mm. This range of fracture size is compatible with empirical observations. For example, Rae et al. (2019) provide scanning electron microscopy (SEM) images of thin sections from the Chicxulub impact structure peak ring. Fracture sizes are variable and dependent on the mineral type, but the fractures within the pyroxene minerals of the granites they studied, which would also be found in basalt, are generally tens to hundreds of microns.

On the other hand, impact-induced pore-space generation on Mars may differ from that on Earth due to differences in impactor and target properties. The average impact velocity on Earth is approximately twice that on Mars and the surface gravitational acceleration is approximately three times higher. The overburden pressure at an equivalent depth on Mars is about one-third that on Earth, implying that residual impact-induced porosity can be supported to greater depth beneath the same size crater on Mars than Earth. This is consistent with numerical simulations of porosity generation beneath large craters under different planetary gravities (Collins, 2014; Wiggins et al., 2022), although the relationship between porosity and gravity is not simple. Conversely, impact-induced pore-space generation will depend on the amount of pre-existing porosity in the crust (Johnson et al., 2021; Milbury et al., 2015), which is likely to be much higher on Mars than on Earth. Residual Bouguer

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anomalies of lunar craters are negative on average and correlate with diameter up to a diameter of about 100 km, suggesting that, in general, impacts on the Moon generate porosity (Soderblom et al., 2015). However, considerable variation in Bouguer anomaly amplitude is observed and many lunar craters exhibit positive Bouguer anomalies indicating that the net effect of impact can be to reduce pore space by compaction rather than create pore space by fracturing and shear deformation (Milbury et al., 2015). On the Moon, there is a correlation between positive residual Bouguer anomaly and regional crustal porosity suggesting that less pore space is created and more is destroyed when the target has higher porosity (Soderblom et al., 2015). If Mars' crust had considerable preimpact porosity, these effects may imply that our fracture area estimate based on terrestrial gravity anomalies is an overestimate of fracture area generation on Mars.

To assess the total surface area produced by all impacts on Mars and how this depends on crater size, we must scale these calculations with crater diameter D. To be conservative, we use the estimate based on simulations of tensile fragmentation and assume that the radius of the fragmentation hemisphere R_F is equal to the crater diameter D. This appears to hold approximately for impactor diameters up to 1-km on the Moon (Wiggins et al., 2019). At larger impactor diameters, tensile fragmentation is suppressed deep in the crust due to overburden pressure. However, as fracture area at such depths is assumed to be closed by overburden pressure via Equation 6, in any case, and the radial extent of the tensile fracture zone will still increase with impactor size, we assume $R_F = D$ at all sizes. We also assume that the average fragment size in the fragmentation hemisphere is constant at $L_H = 1$ m. We do not subtract the crater volume, which is assumed to be small in comparison. This is only an issue for small, simple craters whose depth can be a significant fraction of the fragmentation depth; the depth of large complex craters is very small in comparison with the assumed fragmentation radius (Garvin & Frawley, 1998). We also neglect the effect of impact melting and subsequent cooling. This is a reasonable assumption for all but the largest of martian impact basins ($D > 1{,}000$ km) as the melt volume only approaches the volume of the fragmentation hemisphere for impactor diameters exceeding 100 km (Manske et al., 2021).

For the spallation zone, we assume a radial extent of $2R_F$, a depth before correction for overburden pressure of $0.2R_F$ and a fragment size $L_S = 10$ m, based on simulation results of Wiggins et al. (2019, 2022). A similar geometric model was used by Huang et al. (2022) to elegantly explain the evolution of porosity of the lunar crust by historical impact bombardment.

To determine the cumulative area of fragmentation for all craters on Mars we use the Robbins and Hynek (2012) database of >380,000 Martian craters with diameters of 1 km and greater. The actual number of craters larger than 1 km that have formed on Mars during its history could be considerably greater than the number presently discernible that comprise the Robbins and Hynek (2012) database. The nominal Mars impact flux model of Marchi (2021), for example, suggests that as many as ~70 million craters larger than 1-km in diameter may have formed on Mars, including tens of basins more than several hundred km across. To assess how much this may increase our estimate of the total impact-generated fracture area on Mars, we also consider the cumulative effect of the hypothetical crater size-frequency distribution (SFD) of Marchi (2021) based on the main-belt asteroid population scaled to the surface area and age of Mars. In both cases, we made the simplifying assumption that none of the craters overlap. This is warranted in the case of the current population of craters on Mars given that the cumulative surface area of the craters themselves is less than 1% of the surface area of a Mars-sized sphere. However, this assumption does not account for inevitable overlap of the nearly 200 times higher number of craters in Marchi (2021) impact flux model.

3. Results

Fracture surface area was calculated as a function of crater diameter using the two independent approaches described above and expressed relative to the surface area of Mars, 1.44×10^{14} m^2, calculated as a sphere with mean radius 3,390 km (Figure 2). The purpose of this latter normalization is to provide a conceptualization of the surface area generated by impact compared to the theoretical surface area that microbes could colonize if Mars was a considered to be a flat two-dimensional surface. Comparing our estimated total fracture surface area with this idealized surface area value provides an order of magnitude insight into the scale of the deep subsurface habitat space created by impact compared to the idealized surface area of the planetary body.

For the approach based on numerical simulations of tensile fragmentation (Wiggins et al., 2019), we show the estimated fracture area with (solid black line) and without (dashed black line) the correction to account for close of fracture area due to overburden pressure (Equation 6). This emphasizes the increasing role of overburden

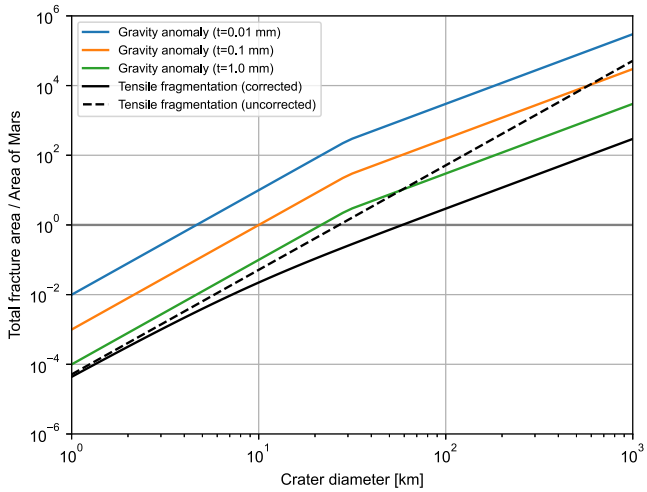


Figure 2. Total impact-generated fracture area as a function of crater diameter. Black lines show estimates based on numerical simulations of tensile fragmentation (Wiggins et al., 2019) with (solid) and without (dashed) a correction to account for close of fracture area due to overburden pressure. Colored lines show estimates based on terrestrial Bouguer gravity anomaly amplitudes for three different assumed fracture widths (t = 0.01, 0.1, 1 mm).

pressure with crater size in limiting fracture. At small crater diameters (~1 km), fracture area scales with D^3, whereas at large diameters (>10 km) fracture area scales with D^2. In this case, craters larger than about 60 km each generate fracture surface area equivalent to the surface area of Mars.

A similar trend is observed for the approach based on gravity anomalies at terrestrial craters. In this case, fracture area estimates are shown for three assumed characteristic fracture thicknesses (t = 0.01, 0.1, 1 mm). In this case, the inflection point at D = 30 km marks the transition from $A \sim D^3$ to $A \sim D^2$ as overburden pressure limits the downward extent of open fracture area beneath the crater. In all cases, the fracture area generated by craters of all sizes is higher than the estimate based on numerical simulations. For a nominal fracture thickness of 0.1 mm, craters larger than 10 km in diameter each generate more fracture area than the surface area of Mars.

A conservative estimate (solid lines) of the cumulative fracture area generated by impacts on Mars is shown in Figure 3, using the method for estimating fracture area based on numerical simulations of tensile fragmentation for the known population of craters larger than 1 km diameter. The fracture area produced by the cumulative distribution of known craters (Figure 3a) is 1.3×10^{18} m^2 or 9,200 times the surface area of Mars (Figure 3c). Using one estimate of the hypothetical population of all craters that may have formed on Mars over its lifetime (dashed lines, Figure 3a; Marchi, 2021) the cumulative fracture area is over 10 times higher at >100,000 times the surface area of Mars.

The size-frequency distribution of known craters on Mars larger than 1-km diameter has a shallow negative slope, $N(>D) \sim D^{-1}$, at small diameters (D < 20 km) and a steeper negative slope, $N(>D) \sim D^{-2.5}$, at larger diameters (D > 100 km) (Figure 3a). Consequently, craters in the size range 20–200 km contribute the most to the total fracture surface area (Figure 3d). Smaller craters (D < 20 km), while much more numerous, are not as efficient at generating fracture area. While >93% of craters in the Robbins and Hynek (2012) database are smaller than 10 km in diameter, they contribute only about 5% of the total fracture surface area generated by all craters (Figure 3b). The simple-to-complex transition on Mars occurs between 7 and 10 km in diameter (Garvin & Frawley, 1998), so the contribution of simple craters to the total impact-generated fracture surface area on Mars is <5%. On the other hand, while the largest impact basins (D > 200 km) each individually contribute a significant fraction of the total fracture surface area there are so few of these basins that their combined contribution is less than that contributed by complex craters in the 20–200 km size range.

Craters in the 20-200-km size range also make the greatest contribution to total fracture area for the hypothetical size-frequency distribution of craters based on the Mars production function of Marchi (2021), which has a similar shape to the population of observed craters in this size range. The hypothetical crater size-frequency distribution (SFD) has a steeper slope at smaller sizes (more smaller craters; Figure 3a), which suggests that these craters might contribute more to the total fracture area than implied by the observed population (Figures 3b and 3d). However, as we neglect the effect of superposition of fracture zones the cumulative effect of these small craters is likely exaggerated by our simple approach. The hypothetical crater SFD also has a shallower slope at large sizes (more large basins; Figure 3a) than observed. If Mars did experience such a large number of mega-basins in its past, they may also have made a significant contribution to the total habitable fracture area on Mars (Figures 3b and 3d). However, as the volume of melt produced by impacts of this scale is comparable to the fracture volume our analysis may overestimate the total fracture volume for these craters.

4. Discussion

4.1. The Importance of Impacts in Martian Habitability

On Earth, impact craters are subject to erosion by wind and the hydrological cycle, burial, and eventual destruction by subduction in plate tectonics. The lack of plate tectonics, limited burial, and the more subdued hydrological cycle, at least since the Hesperian, mean that craters on Mars are much better preserved. Thus,

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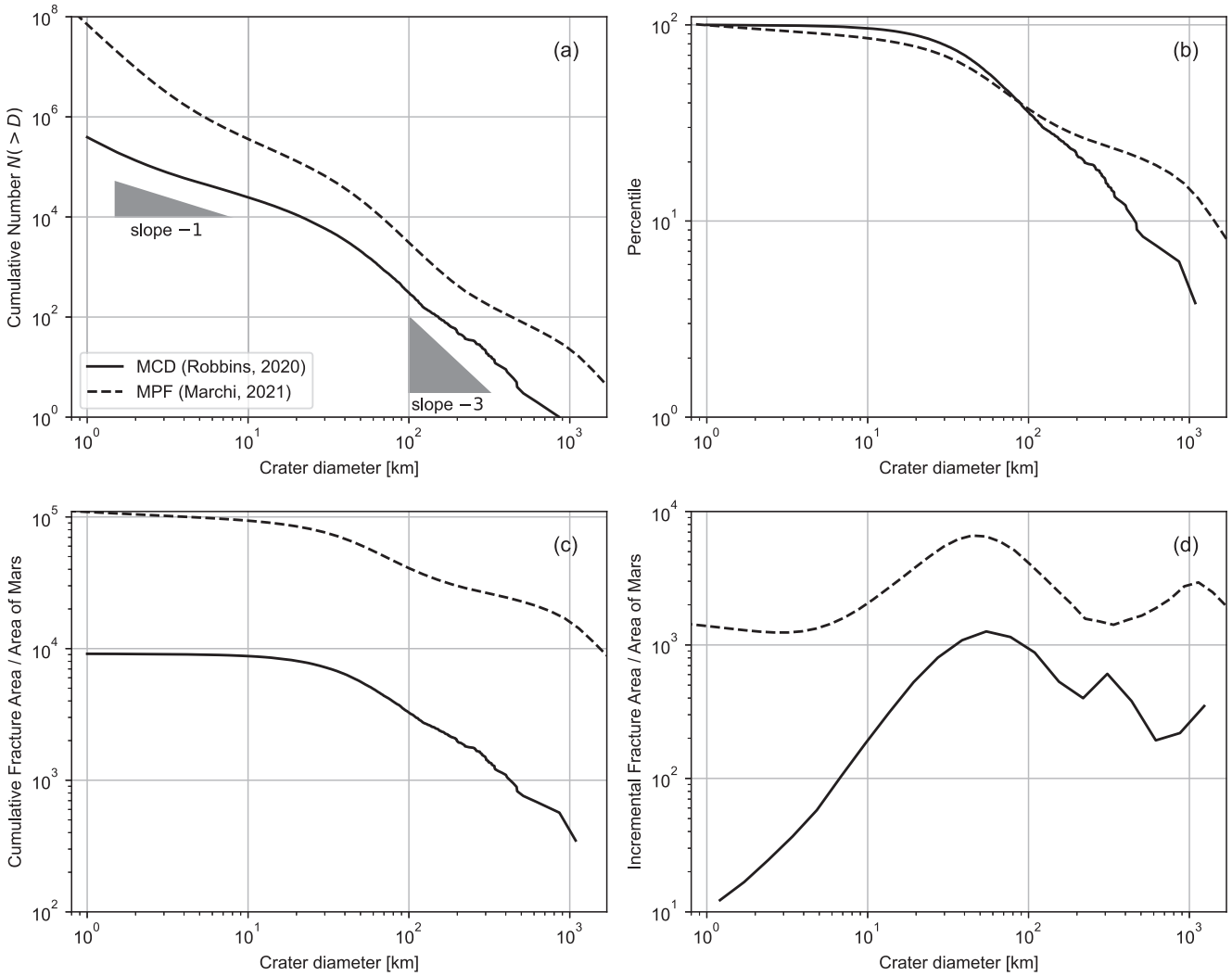


Figure 3. Cumulative fracture area generated by known craters on Mars (solid lines) and hypothetical population of craters that may have formed over Mars' history (dashed lines). (a) Cumulative size-frequency distribution of craters on Mars larger than 1-km diameter (Robbins & Hynek, 2012) and the Mars crater production function model of Marchi (2021) based on the SFD of main belt asteroids and scaled to the surface area and age of Mars. (b) Total fracture area generated by craters with diameter greater than D as a percentage of the total fracture area generated. (c) Total fracture area generated by craters with diameter greater than D, normalized by the surface area of Mars, as a function of crater diameter. (d) Relative contribution to the total fracture area made by craters of different sizes, normalized by the surface area of Mars.

although the influence of impact events and craters on planetary habitability is considered ephemeral on Earth (although it may not have been in the early history of the planet; Osinski et al., 2020), on Mars, impacts substantially shape the conditions for habitability. In this study, we have sought to make a first-order estimate of the fracture space that might have been created by impacts to quantify the possible effects of impacts on martian subsurface habitability.

Our numerical calculations suggest that the surface area generated by impacts into the deep subsurface may constitute the equivalent of 9,200 times the surface area of Mars, up to 100 times this value calculated using gravity anomalies in terrestrial impact craters. These numbers illustrate the considerable uncertainties that remain, some of which we discuss below. However, whatever approach we use to estimate the area of the fracture zone, impact-induced fracture space constitutes a potentially vast and significant surface area for microbial activity.

Although complex craters are numerically a minority of craters on Mars, they dominate the potential habitable fracture surface area since they dominate the crater-induced fracture volume, at least using the assumptions considered here. Although >93% of craters in the database developed by Robbins and Hynek (2012) are smaller

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than 10 km in diameter, they contribute only about 5% of the total fracture surface area generated by all craters. The fracture area we present here is based on the total observed number of craters in the present-day (Robbins & Hynek, 2012) or the hypothetical total number of craters to have ever formed on Mars according to a recent model of crater production (Marchi, 2021). Over Martian history, this fracture area will have increased because of the accumulating number of craters and concomitantly, it will have declined because of erosion, occultation of old fractures, etc. However, given that the impact flux was much higher during the Pre-Noachian and Noachian (Marchi, 2021) than the flux over the most recent 3 Gyrs we expect that a large proportion of the fracture space was emplaced during the first ∼800 Myrs of Mars' evolution. A more time resolved analysis during this period when more surface and near-surface liquid water was available (i.e., conditions were more clement for life) would be of interest.

These calculations also show the potential surface area for preservation of organics and any putative signatures of life. Fractures are prone to mineralization over time which, while occluding habitable volume, can also favor the preservation of biosignatures (Ivarsson et al., 2013), suggesting a way in which impact events might substantially increase the space available for preserving signatures of ancient life if it was ever on Mars and showing that impact fractures are a promising target in the search for testing the hypothesis of past life on Mars. Often this mineral occlusion is caused by post-impact hydrothermal processes (Kirsimae & Osinski, 2012; Osinski et al., 2013), with the hydrothermal systems themselves providing fluid flow and energy and nutrient sources for microbial communities which could contribute to the inventory of biosignatures.

4.2. The Impact-Sphere: Help or Hindrance to Martian Habitability at the Planetary Scale?

Intuitively, we would expect that the fracture surface area generated by impacts would lead to an overall increase in the suitability of the surface and subsurface for life, by providing pathways for fluid flow that carry nutrients and redox couples for life, as observed in the terrestrial environments. For example, in the Haughton impact structure (Canada), shock metamorphism of crystalline basement rock leads to increases in available fracture and pore spaces for cryptoendolithic (Cockell et al., 2002; Pontefract et al., 2012, 2014) and chasmoendolithic (Cockell et al., 2003) organisms. More specifically, an increase in light transmission through these spaces improves the habitat for photosynthetic organisms. Microbial colonization can also be enhanced in evaporitic minerals produced by impact, such as sulfates (Parnell et al., 2004). Likewise, in the deep subsurface of the Chesapeake and Chicxulub impact structures, there is evidence for enhancements of microbial numbers in regions of increased porosity associated with the formation of impact breccias or at geological interfaces associated with the intrusion of impact melts into pre-impact rocks (Cockell et al., 2009, 2021). These enhancements have been attributed to improved fluid flow through the subsurface.

Extrapolating these observations to Mars, we might speculate that impact-induced fracturing would enhance the habitability of the Martian subsurface. The potential biological relevance of groundwater flow in the subsurface of Mars has already been pointed out by Michalski et al. (2013) who emphasize the importance of flow for conditions conducive to the origin of life. Investigations of the effects of impact processes on surface and subsurface microbial communities on Earth support such a hypothesis.

One example of an influence of impact-induced fracturing on deep subsurface habitability on Mars is the production of hydrogen. Hydrogen is an electron donor that can sustain life, for example, in combination with carbon dioxide in methanogenesis or in anaerobic metabolisms such as sulfate and iron-reduction. Hydrogen can be produced by the radiolysis of water in subsurface fracture spaces (Dzaugis et al., 2016, 2018; Lin et al., 2005; McMahon et al., 2016). Water transport through the fractures, for example, through hydrothermal systems (Osinski et al., 2013) can generate H_2 via the aqueous alteration of olivine in sufficiently warm regions of the crust (which may be relatively shallow while the heat of impact slowly dissipates) (Neubeck et al., 2011).

The availability of hydrogen will change over time after any given impact as fractures become mineralized and occluded. The biological accessibility of the hydrogen will depend on its steady state production rate and its accessibility to a biota, itself determined by the accessibility of the fractures to organisms, the rate of fluid flow and the extent to which other requirements for life (e.g., electron acceptor, CHNOPS elements) limit life. Nevertheless, McMahon et al. (2016) present empirical evidence for concentrations of hydrogen production in seismic events sufficient to support biological growth, suggesting analogously that impact-induced fracture networks would provide enhancements in hydrogen production for microbial growth.

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In addition to generating fluid flow conducive to the release of nutrients or elements and molecules useful in redox couples, such as hydrogen, impacts may generate long-lived hydrothermal systems which would enhance habitable volume by melting ice in the subsurface. Some of these hydrothermal systems would have persisted for millions of years (Abramov & Kring, 2005).

However, the hypothesis of impact-induced improvements in habitability must be tempered by other observations. During the transition from the Noachian into the Hesperian and into the Amazonian, the abundance of surface liquid water decreased. Mars transitioned into a state in which salt and brine formation seems to have been extensive, with evidence for chlorides (Glotch et al., 2010; Osterloo et al., 2008, 2010) and sulfates (Bibring et al., 2007; Gendrin et al., 2005; Karunatillake et al., 2014; Morris et al., 2006) in locations across the planet. Some of these salts are known to support life on Earth. For example, concentrated sodium chloride brines host microbial communities, although their microbial diversity is often low on account of the special adaptations required to live in them (Kamekura, 1998). Furthermore, brines composed of magnesium sulfate have sufficiently high water activity to support life (Crisler et al., 2012). However, some of brines, such as iron sulfate-rich brines or perchlorate brines, may have water activities and/or ionic strengths outside the limits of life, rendering them uninhabitable to life as we know it (Fox-Powell et al., 2016; Tosca et al., 2008).

The existence of a pervasive impact-fracture network within the subsurface of Mars could therefore have provided a pathway for Hesperian and Amazonian brines to flow into the subsurface to render some subsurface environments uninhabitable (while at the same time contributing to bulk water loss from the planet). Furthermore, brines carry high ion loads, which if precipitated within fracture networks, may cause secondary mineralization, closing pore spaces and fractures to microbial access. This hypothesis would be consistent with observations of impact structures on Earth. For example, Henkel (1992) describes the electrical conductivity of the 52-km-diameter Siljan impact structure (Sweden) and shows how the electrical conductivity increases toward the center of the crater, which is interpreted to represent conductive briny fluids in the impact fracture networks.

We know that on Earth, subsurface continental evaporitic settings can host brines that are too extreme for life, for example, on account of high concentrations of magnesium and chloride ions, and that these brines flow through fractures to render these networks uninhabitable. Locally, these fluids set a subsurface limit to life at much shallower depths than the geothermal gradient (Payler et al., 2019). Analogously, impact fractures that provide a conduit for extreme brines may set subsurface limits to habitability on Mars.

The degree to which impact fractures are beneficial or deleterious to life will depend on the characteristics of the fluids that pass through them, which may be dependent on location and the time, since we observe geochemical diversity across the surface of Mars.

These observations raise a number of hypotheses that can be tested. For example, the hypothesis that the pervasive impact fractures represent a planetary scale determinant of habitability can be tested by examining the depth and geographical distribution of Martian subsurface impact fracture networks by deep drilling. The hypothesis that these fracture networks helped or hindered life can be tested by examining the mineralogy of impact fractures in the subsurface to determine their history of fluid flow and the past or present existence of brines and precipitated salts. These data can be used to calculate the physicochemical environment in impact fracture networks with respect to life (including water activity, ionic strength, and availability of redox couples and nutrients) to determine whether the fluids potentially enhanced habitability in the fracture networks or reduced it.

Finally, in the very long term, drilling in many different locations on Mars will allow us to map in three-dimensions the way in which impact fracturing influences habitability in the Martian deep subsurface on the planetary scale. These hypotheses provide a motivation for Mars missions that can access the subsurface environment, carry out in situ mapping of the core holes, and retrieve core material.

4.3. Uncertainties in the Calculations

Our calculations are subject to uncertainties. However, these uncertainties themselves suggest several avenues of research that would advance quantitative assessments of the effect of impact fracture networks on the habitability of Mars. Specifically, they include:

(1) The strength properties of different Martian rock and sedimentary types under impact will influence the threshold of rock failure and fracture formation (Collins et al., 2004) and could be improved. Investigations

on the mechanical and fracture properties of Mars analog materials from sandstones to mudstones, based on observations of materials at Gale Crater, Mars, show that parameters such as fracture toughness and energy vary over an order of magnitude (Kronyak et al., 2020). The calculations will also be affected by the characteristics of the fractures generated by impact. Wide fractures will take up more volume within rocks and reduce the corresponding surface area, all other factors being equal. More quantitative theoretical and laboratory studies on Mars analog rocks and minerals would refine our knowledge of fracture sizes and their microbial accessibility for given shock pressures, similarly to experiments undertaken in gabbro (Polanskey & Ahrens, 1990).

(2) Microbial studies have shown that low porosity crystalline rocks such as gneiss become more accessible to microorganisms as the shock energy is transformed into fractures and permeable vitrification features (Cockell et al., 2002; Pontefract et al., 2012, 2014). However, initially high porosity rocks, such as porous sandstones, can become less accessible as the impact energy causes pore closure and/or glass formation (Cockell & Osinski, 2007). These complexities of specific mineral types will influence microbial colonization. A better understanding of them, especially in Mars analog rocks such as basalt and its weathering products, would improve the ability to link fracture calculations with proposed biological effects.

(3) The initial permeability of different rock types will influence the subsequent extent of fracturing and permeability with depth. To more exactly quantify how impacts changed the space available for life, we need to know the porosity and, more importantly, the permeability of un-shocked Martian rock types, and to consider how the heat and shock of impact affect these parameters.

(4) We have not taken into account large-scale fracture networks, such as the radial and concentric fracture networks around a crater (Rodriguez et al., 2005). These have been mapped in the crater walls of the ∼1.8-km-diameter Lonar impact structure (India), one of the few structures formed in basalt, but the subsurface extent of the fracture network has not been modeled or measured (Kumar, 2005). According to numerical simulations of large impacts on the Moon, Earth and Mars, the shallow spallation zone around the crater may dominate the total volume of pore space created by the impact (Wiggins et al., 2022), although the larger spacing and wider fractures in this zone may mean that it does not dominate in terms of fracture area. A detailed surface and subsurface study of the fractures within Lonar crater and other structures in basaltic target would be of considerable value. Nevertheless, we note that the surface area of these large-scale fractures is likely to be exceeded by the pervasive small-scale fractures, the focus of our estimates here.

(5) We have assumed that none of the craters overlap and there is no influence of one crater fracture structure with another. This simplification could be overcome by improved mapping of craters on Mars and eventually the subsurface investigation of their fracture networks.

4.4. "Analog" Studies Reconsidered and Mission Implications

The much greater extent of impact-fractured rocks on Mars compared to Earth underscores a more general principle of investigating extraterrestrial habitability. In the last decades, there has been focus on "analog" studies, which emphasize the search for environments on Earth that are similar to environments elsewhere. Our discussion emphasizes the importance of investigating phenomena on Earth that are rare, such as impact fracturing, but might be dominant factors in shaping habitability elsewhere. Furthermore, as we illustrate here, there may be multiple disanalogous factors at play. The pervasive impact fracturing on Mars may have propagated life-limiting concentrated Hesperian and Amazonian brines into the Martian subsurface, which themselves are the product of Mars's dissimilar geological history compared to Earth. In other words, we should focus on the complex interactions of potentially multiple physical and chemical factors that together produce environments with no analogous examples on Earth.

These observations have implications for missions. Instead of constructing hypotheses based solely on terrestrial analogs, we should also construct hypotheses based on specifically extraterrestrial conditions. For example, the hypothesis that pervasive impact fracturing could either have enhanced habitability by stimulating fluid flow or reduced it by stimulating the hydraulic conductivity of life-limiting brines, or a combination of both, affects the types of instruments that might be chosen to test these hypotheses. It might encourage a focus on instruments that can map fractures at small scales and can reliably identify different evaporitic minerals at small resolution within these fracture networks.

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5. Conclusions

Calculations on the extent of the shell of impact-fractured rock on Mars suggest that impact-induced fracturing has pervasively shaped the habitability of the subsurface, generating vast networks of microbially accessible fracture space. Although empirical observations in impact craters on Earth suggest that this should improve conditions for microbial growth, these same fracture networks may provide conduits for the movement of life-limiting brines, thus restricting habitability. Deep drilling into Mars will allow us to directly investigate how impact cratering has influenced subsurface geological and geochemical conditions at local and planetary scales, and thus the conditions for prebiotic chemistry and life.

Data Availability Statement

The Mars crater data was obtained from the Mars Crater Database (https://craters.sjrdesign.net/). These data were updated in 2020 from Robbins and Hynek (2012). The models and data derived from these crater data are documented in a Jupyter notebook and are available in Collins and Cockell (2024).

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