

MARS CHRONOLOGY DERIVED FROM CRATERS HETEROGENEITY AT GALE CRATER

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Abstract. Craters sample into diachronic surfaces and different depths on Mars and other planetary surfaces. These surfaces are affected by cosmonuclide radiation that offers one of the most reliable age anchors to date. Craters also accumulate, evolve and display an universal characteristic that can be measured at any scale, regardless of the geologic unit they sample, in the form of the heterogeneity parameter (Căpitan, 2021). Here we use an age equation, which is based on the measurements of craters diameter, depths and area they occupy, to derive the ages of deposits that are sampled by medium-scale craters (meters to few hundred meters in diameter). We show that units sampled by the deepest craters near MSL exploration area are formed during the early stages of Gale crater formation before 2870 Ma. In contrast, units sampled by shallower craters were formed during the stages that correspond to the time of sediment recycling and lithification periods, near 2129 Ma to present. Given the heterogeneity of initial formation conditions of craters of diverse diameters and their different depths of sampling, our proposed synchronous ages with ground-truth ages has the potential to redefine the paradigm of using the impact crater morphometry as a tool to date the planetary surfaces.

Key words: space sciences, solar system, planets .

1. INTRODUCTION

The absolute age of Martian geological events will not be fully understood until the relative Martian chronology derived from stratigraphy is tied to an absolute chronology via cosmonuclide and radiometric dating of Martian rocks (Cohen *et al.*, 2019). Results to date involve concurrent work on orbital mapping and rover measurements, crater counting, mineralogic data interpretation, and orbital dynamics of planetary bodies. The first type of data that offer us insights on the history of crust formation, volcanism, cratering and landforming events are the Martian meteorites. They also provide the most accurate proof of the geological ages on the planetary surfaces (Moser *et al.*, 2013; Nyquist *et al.*, 2001; Udry *et al.*, 2020), but no location of meteorites sources (Váci and Agee, 2020). Then, the orbital photogeologic mapping and crater counting techniques provides context and offer a procedure to date the planetary-scale units across Mars (Hartmann and Neukum, 2001; Hartmann, 1971; Werner and Tanaka, 2011; Robbins, 2022). Zircon dating of Martian mete-

orites provides proof on the antiquity of the lithology derived from initial Mg-alkali magmatism, while orbital dynamics studies constrain the impact bombardment periods on Mars (Gomes *et al.*, 2005; Costa *et al.*, 2020; Marchi, 2021; Nesvorný *et al.*, 2023). Like on the Moon with Apollo, Luna and Chang’e samples, and on Itokawa and Ryugu with Hayabusa samples, on Mars, the in situ measurements at Gale give us the first ground-truth ages on both the mineral formation (Farley *et al.*, 2014; Martin *et al.*, 2017) and exposure of rocks (Vasconcelos *et al.*, 2016; Le Deit *et al.*, 2013). Between these two events, the geologic units have been deposited, lithified and scoured over billions of years (Grotzinger *et al.*, 2014; Edgett *et al.*, 2020). On top of these deposits, craters sample to depths of decimeters to decameters near MSL (Mars Science Laboratory) exploration area, and on hundreds of meters on the northern floor of Gale and elsewhere. Most of these craters look degraded by eons of resurfacing (Newsom *et al.*, 2015), which is also an indication of the relative age of the deposits they sample. A measurable variable of the relative age of a cratered surface is the crater depth-to-diameter (d/D) relationship. This relationship offers some explanations on the prolonged steady-state evolution of craters in the d/D range near MSL exploration area or elsewhere. The idea of crater degradation as a time indicator for Mars is not new, dating back to the Viking missions (Hartmann, 1971; Chapman, 1974) and continued thereafter (Smith, Gillespie, and Montgomery, 2008; Michael and Neukum, 2010; Newsom *et al.*, 2015; Watters *et al.*, 2015; Breton *et al.*, 2022), but none to date offers a calibrated age among craters sampling depths, their evolution, and the existing ground-truth or the meteorite ages. Given the importance of the depth sampling by individual craters in exposing the rock formations of different ages, it is somehow surprising that so little research has been done to address this relationship. Craters sample at all possible depths and onto diachronic surfaces, exposing the rocks in a way that is similar to the vertical denudation (Stewart and Valiant, 2006). A large body of work is aimed towards proving the correlation between mass and force of impactors and craters depth sampling at all scales, work reviewed by (Melosh, 1989; Grieve, Osinski, and Tornabene, 2014) among others. Here we explore the equally possible and ubiquitous situations where: (1) crater samples at depths of few decimeters where cosmogenic nuclides penetrate (depth sampling offers an anchor chronometer), and (2) craters also expose decameter-deep rocks that were formed earlier than the exposure of surface by denudation. We examine the smaller craters that sample within the three medium-size craters ($D \leq 200$ m) that are located on different geologic and morphologic units near the MSL exploration area (craters 1-3, Figure 1). Regardless of the craters’ dimension and location, the morphometric heterogeneity of craters is a fact (being the resultant of random formation of craters by diverse size impactors), and can be measured at all spatial scales. Here we use the heterogeneity parameter $\bar{h}$ that is a proxy for the evolution of craters to develop an improved chronology on the MSL exploration area and beyond,

on the northern crater floor of Gale at HiRISE DEM spatial resolution (horizontal resolution ~ 1 m). Even if it is used here differently but complementarily than has been proposed by (Căpitan, 2021) at lower spatial scale resolution of HRSC and MOLA datasets, see the Method below, we demonstrate that $\bar{h}$ is a chronometer, and use a mathematical relationship to relate it to the craters' depth sampling, and to the existing ground-truth ages. Three constraints set up the framework of the present study. Firstly, the cosmogenic nuclides document the history of rock exposure and can be measured on rocks at surface and extrapolated several decimeters in depth (Le Deit *et al.*, 2013). Cosmic-ray exposure (CRE) is the same for rocks that are exposed at the same time, regardless of their location, being one of most reliable chronometers used so far on the planetary surfaces. Although exposure ages of outcrops vary within the MSL exploration area (Farley *et al.*, 2014; Vasconcelos *et al.*, 2016; Le Deit *et al.*, 2013), the longest exposures of surfaces (closest in theory to rock formation ages) were measured at the southern edge of Aeolis Palus at Mojave and at Quella on the Aeolis Mons, and within the same age range. Rock units are differently exposed by denudation and have different CRE within meters. Similarly, small craters sample rocks to the same depths but most likely at different times. Nonetheless, from present perspective surface rocks are sampled at the same depth range by both the small-diameter craters and cosmonuclides. Secondly, bolides that fall into Mars are also highly energetic events that form craters several decimeters to decameters in depth into the pre-existing rocks in a strength-to-gravity impact scenario (Stewart and Valiant, 2006; Daubar *et al.*, 2014). Thirdly, we use the concept of equifinality where the entire population of craters is considered to form the heterogeneity parameter value (Căpitan, 2021). Craters diameters, depths and area they occupy reflect the ongoing formation, evolution and accumulation to the present state in form of an equivalent energetic manifold.

Craters sample the study area randomly and at different depths, but there is a relatively fresh crater that is located in the same geographical area as the sites where *in situ* ages are provided (crater 1, Figure 1).

This crater samples the surface and exposes the rocks on a cratered surface (CS Unit, Anderson and Bell, 2010), and onto a rock unit that was formed before the rock unit at Mojave, because this crater is located 60 m below in altitude (Figure 3). Hence, the newly proposed chronometer should indicate an age difference. We repeat the morphometry measurements for another crater that is formed on the lower Mount Sharp within Murray formation to the south-west (crater 2, Figure 1), and test if the method reveals an older age as the stratigraphic interpretation shows, using the age anchor at Quella as calibration (Le Deit *et al.*, 2013). We finally predict that the ages proposed here correlates on broader regions beyond the MSL exploration area. We measure the morphometry of another larger crater near the Peace Valis alluvial fan within the same distance range from the locations of the CRE measurements

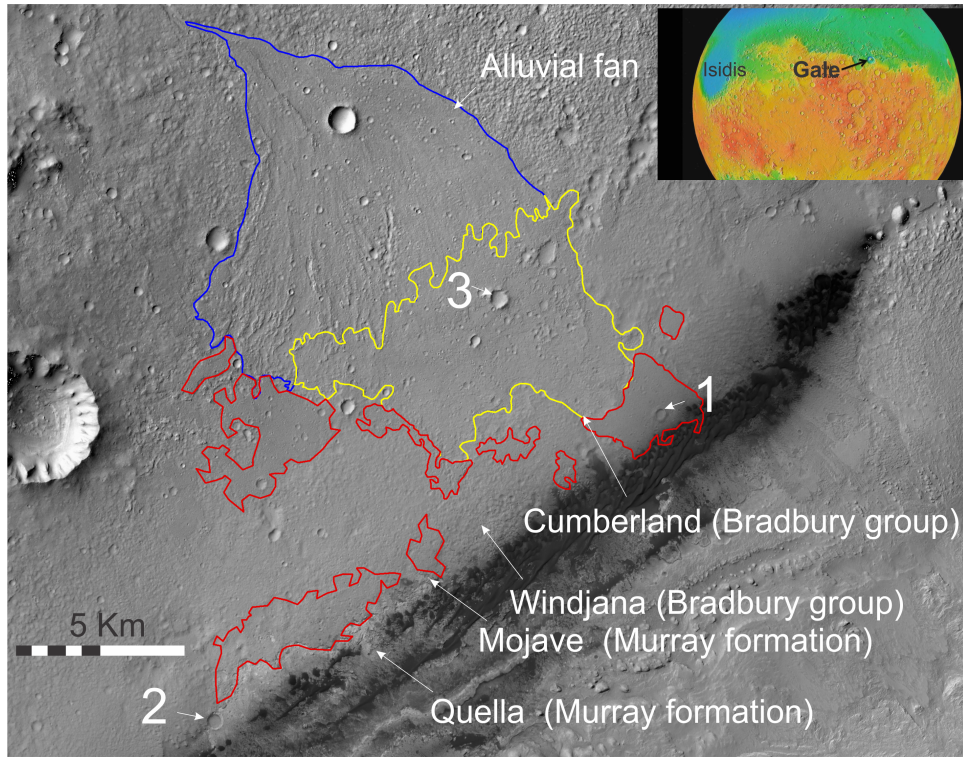


Fig. 1 – Map of the study area and position of sample locations and their stratigraphic context. Location of major surface units of Peace Valis fan (blue), Yellowknife Bay's bedded fractured formation (yellow), cratered surface unit (red) are shown (after Anderson and Bell, 2010). Location of larger craters 1–3 that are used here are indicated in white numbers. Background image CTX D02_027834_1748_XN_05S222W centered at -4.5 degrees S, 137 degrees East. Inset is the DEM globe of Mars with Gale location and Isidis basin for reference. (Credit: NASA PDS Node).

(crater 3, Figure 1). As craters samples deeper into the surface rocks, we expect that the method will predict older ages (Figure 2, Table 1). We calculate the $\bar{h}$ parameter for craters of diverse diameters, formed at different times, and for a different number of superposed craters (Table 2). None of these initial constraints suggest a trend or a consistency in the age outcomes, hence, the importance of discovering synchronous and/or consistent ages on the same lithostratigraphic units that are distributed regionally. We thus aim to ascertain for the first time the age of sampled geologic deposits on Mars, on the regional scale of northern Gale, using the available ground-truth ages.

2. METHOD

Calculation of the heterogeneity parameter relies on identification and measurements of craters morphometric characteristics from orbital imagery and digital elevation models (DEMs). The craters morphometry and associated morphologic appearances represent the final stage of their accumulation and evolution, as seen currently on any cratered terrain. Differences in accumulation, diameters and depths of craters are resultant of heterogenous formation of these craters in space and time. The High Resolution Imaging Science Experiment (HiRISE) imagery and DEMs from the Mars Reconnaissance Orbiter [MRO] (Malin *et al.*, 2007) are used to identify, locate and extract the morphometry of craters manually. Context Camera (CTX) D02_027834_1748_XN_05S222W image is used to map larger surface units using previous map boundaries (Anderson and Bell, 2010), identify the locations where the ages were measured, and the position of the larger craters on which the present paper focuses on. Crater morphometric extraction of altitudes was performed manually on HiRISE DEMs available on the LPL/University of Arizona website (<https://www.uahirise.org/dtm/>). Four DEMs and associated orthoimages were used to extract the craters location and their morphometry: DTEECs: (023957_1755_024023_1755_U01; 010573_1755_010639_1755_U01; 009650_1755_009716_1755_U01; 024234_1755_024300_1755_U01). All imagery and DEMs were georeferenced in ESRI ArcGIS (for visual crater extraction on imagery, DEM rendering and topographic profile extraction (Figures 3–4). Craters morphometry extraction are presented on Figures 5–6 and related Tables. Orthoimages were superposed on DEMs to identify the small craters and delineate the rims of the larger craters. Heterogeneity parameter values were computed using the manifold and central location of craters' morphometry that are constructed in the Golden Software Surfer (See craters morphometry data in the Tables 3–6 and manifolds on Figure 7). Heterogeneity parameter construct has been used to plot the morphometry of craters across Mars and to define a new construct that relates craters entropic state to the relative age of the geologic units (Căpitan, 2021). Within any surface where craters form, evolve and accumulate, their size, depth and area are added cumulatively to construct a three-dimensional manifold using each measured morphometric characteristic (crater diameter D , crater depth d , and area of craters A).

Here instead we use the same manifold construct on individual medium-size craters ($D > 200$ m), as they also represent local-scale geologic units and measure as well the morphometry of smaller craters within the larger ones. Smaller craters form everywhere, but we investigate the ones inside the largest ones (to provide the superposition relationship). Therefore we consider all craters that superpose on the initial crater, including the rim, even if even touching it partially (Figures 5–6).

The manifold construction follows the same rule, but the outcome is different

in a way that the largest crater itself shapes the manifold differently on all axes, but mostly on the z axis, as the crater diameter and depth are several times larger than the correspondent of the smaller craters. The largest craters are the geologic units themselves, on which other craters accumulate, thus z is >100 percent. The base of the manifold remains also a square (Figure 7). The entropic state of the craters evolution has a different meaning for the same reasons, where the largest crater evolves differently than the population of smaller craters. Nonetheless, the manifold construction enables both the calculation of the chrono-morphologic volume, and the entropic state variable. The resultant $\bar{h}$ parameter values are several orders of magnitude higher than the values of the manifolds for the larger crater population that form over a larger areas (Căpitan, 2021) (Supplementary Table 5 for the regional-scale units inside Gale, and here on Table 2). This does not imply that the local units are older than the large-scale ones, where multiple craters of larger sizes sample deeper the rocks. Instead, it implies that at the local-scale the heterogeneity parameter anchors in a different way how craters form, accumulate and evolve, when is compared to a population of craters that is spread on a larger area. This difference in magnitude of impact craters and scale of analysis is reflected in scaling down the $\bar{h}$ parameter values for individual craters, as exemplified in the following section. In summary, craters sample the local geologic units at different depths, at different times and into the exposed deposits that have different formation ages. Here we explore the situation where we can use the heterogeneity parameter of craters to calculate the ages of rock units that are sampled by the largest craters. We use the CRE exposures as chronometers, and propose a model in which the energy that is spent to form craters of different depths is seen as a proxy for age calibration.

3. RESULTS: FINDING AN AGE EQUATION

We consider the craters sampling as a natural process that exposes the existing rock units (Figure 2).

Cratering is a highly energetic process. Energy involved to create craters grows exponentially from small impactors to large impactors, because the bolides volume and weight increase exponentially as well (Melosh, 1989; Stewart and Valiant, 2006). The mass and volume of impactors grow from several kilograms and cubic decimeters that form craters meters in diameter and to decimeters to at most few meters in depth, to tons and cubic meters or more that form craters several hundreds meters in diameter and tens of meters in depth.

This is expressed as an increase in depth Δy on the local stratigraphy (Figure 2a) between y_0 corresponding to the depths of the smaller craters and that of y_n corresponding to the depth of the largest crater(s) (*e.g.* it is calculated for all craters

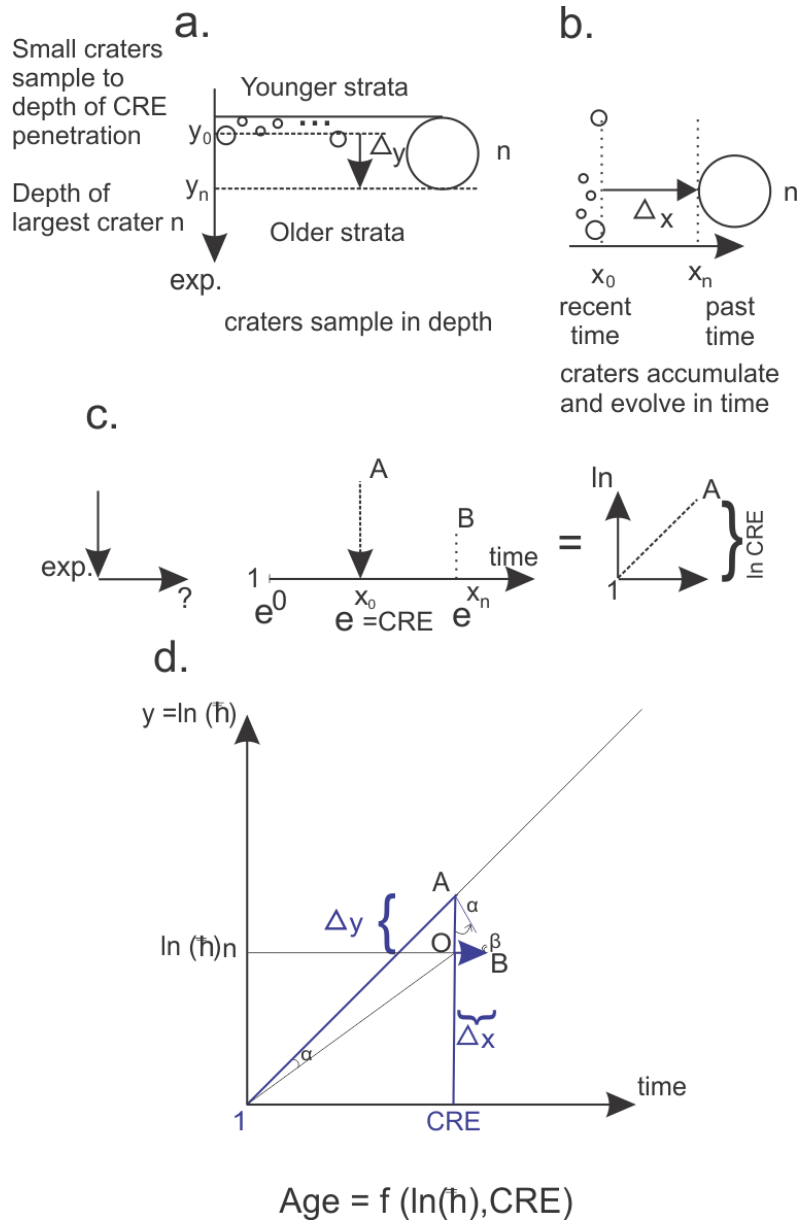


Fig. 2 – Age calibration of the heterogeneity parameter ($\bar{h}$) measurements. a.-c. diagrams showing model construction sketch; a. Model of crater sample depths into local stratigraphy due to different force of gravity-to-strength cratering b. Corresponding time difference between formation of small craters and the largest one c. Equivalent time-frame diagram construction (see main text) d.

Calibration of the heterogeneity parameter with the cosmonuclide exposure age. The calibration means plotting of known in situ age at A and its translation to intersect the heterogeneity parameter $\ln(\bar{h})$ horizontal line. For the θ angle translation we propose an equivalent displacement along the horizontal $\bar{h}$ line (see main text), to obtain a calibrated model age of a geologic unit that is sampled by the largest crater.

marked in Figure 1). We reiterate that as the mass, volume and speed of the impactor increases exponentially, there is a corresponding exponential increase of the diameter and depth of any crater in a strength-to-gravity impactor situation that we explore here. Also, the target surface is considered to be the same within the area of interest, where smaller impact craters accumulate within any larger craters. Similarly, there is a time difference between the formation of the smallest and the larger craters. Because the largest crater ‘n’ samples into the altitudinal range beyond the few centimeters to several meters of the ongoing surface exposure, and deep into strata that was deposited back in time, we express the difference in time as Δx (Figure 2b). Up to this point there is no measure unit of either the time of crater formation nor the force of cratering, although a correspondence between craters diameters (what we measure on maps as equifinality of cratering) and the force of impact cratering can be calculated. As craters sample with an exponential increasing force between y_0 and y_n , we propose here representing the time in equivalent exponential values on the x axis: x_0 and x_n (Figure 2c). We note that the anchor age reference x_0 can be expressed as $e^{\ln[CRE]}$ that returns the true age value in million years (Ma). The other age anchor on the time axis x for which we can return an age value is plotted as an exponential as well, where $e^0 = 1$ means present time. We have to find the corresponding exponent x_n back in time that has to reflect the hypothesized formation time of the older rocks being sampled by deeper craters. The only available information of the time of strata emplacement is the relative stratigraphy of the nearly horizontal local sedimentary units. The question here is how to relate the depth of rock units being exposed in an instant back in time to the depth of strata affected by more recent and prolonged cosmic ray exposure. Rocks are sampled by both cosmonuclide radiation and impact craters at different depths, but sometimes these depths correspond. From the present perspective we see both sampling as an equifinality. The age relevance for both processes such as the exposure of surface rocks and sampling by impact craters is straightforward. Surface rocks have a formation time and an exposure time, regardless of the difference between the two. Craters sample rock units that are already formed at a certain time. Although CRE can differ within several square meters, loose debris inside larger craters or elsewhere, or poorly lithified rocks (extra-formational sediments, Edgett *et al.*, 2020) can be exposed on Mars several tens to hundreds of million years without being disturbed. The indurated or primary rocks can resist more, up to the time of their deposition. We propose a graphical representation for which the correspondence between the cratering sampling depths and the CRE age anchor is framed to be equivalent. For any Δy (e.g. change in depth) there is a correspondent Δx (e.g. change in time). From the origin on the vertical axis, we plot the exponent at which a value is raised to return the real time, which is $\ln[CRE]$. Seen from the depth and force of crater sampling, it corresponds to the y_0 position on the depth of cratering axis on Figure 2a. The equivalent

time–frame representation is the right–angle isosceles triangle $\widehat{1X_0A}$.

The novelty of our approach is to plot the heterogeneity parameter in natural logarithmic terms on this equivalent time–frame, in the same position as the y_n on the Figure 2a. Extracting the natural logarithm of $\bar{h}$ scales down the magnitude when compared to $\bar{h}$ that is computed on larger areas and for multiple craters (Căpitan, 2021). The $\bar{h}$ value of crater 1 is 6811612. When is scaled down to $\ln \bar{h} = 15.73$ it becomes proportional in value to the $\bar{h}$ for the scale and size range of craters that form on the larger Aeolis Plain. As an example, by comparison, the value of $\bar{h}$ parameter is 136395 for 29 craters on the Crater floor unit 1, on which all of the measured craters have diameters of 700 m or more (Căpitan, 2021); see for comparison the size of crater 1 on Figure 1 relative to the size of the crater on top of the alluvial fan, and to the size of the largest crater to the west, both of which being used for the heterogeneity parameter calculation of crater floor 1 in (Căpitan, 2021).

When craters sample into the stratigraphy of surface rocks, they create a discontinuity in the geologic column. Nonetheless, there is a continuity of evolution of craters morphometry, and in addition, for larger craters there is a subsequent action of smaller cratering inside their rims. This continuity is captured by the value of the scaled heterogeneity parameter $\bar{h}$. Stratigraphically, this is the position from which the largest crater started to evolve back in time, has the continuity of evolution, and on which other craters accumulated, forming the heterogeneity that we measure today from the morphometry of all craters (Figure 2d). Although it happens in an instant, and is not the same as the prolonged vertical erosion or exposure, craters sample the rock formations that were formed earlier in a similar way, exposing the local stratigraphic column.

We obtain a simple trigonometric relationship between the independent variable (time) and the dependent one (the scaled heterogeneity parameter $\bar{h}$). The time correspondent of each scaled $\bar{h}$ parameter measurement for the three craters is then equated as a function of the surface exposure age multiplied with the displacement from it (arrow OB, Figure 2d), labeled Δx , where Δx is defined by the trigonometric relationship on the adjacent triangle $\widehat{1X_0A}$, between Δy , α , and the 45 degree opposite angle to the side AO. As the line AO represents the CRE age on the x (time) axis, the angle α is adjacent to line AO. The age equation is expressed as:

$$Age = e^{\ln CRE} \cdot e^{\Delta x} - 1, \quad (1)$$

where Δx is given by equation $\Delta x = \frac{\Delta y \cdot \sin \alpha}{\sin \beta}$. The parameters used to calculate the age calibration for the six craters are provided in Table 1.

All our calibrated ages are older than the radiometric age measured at Mojave and younger than the radiometric ages at Cumberland and Windjana. The smallest and the freshest crater samples only 15 m in depth and into an exhumed unit (CS unit)

Table 1

The model ages for the three craters in Figure 1. There are two available *in situ* anchor ages: Mojave 2, which is 1060 ± 330 Ma at the edge of Aeolis Plain and upper end of Bradbury group, and Quella (marked with asterisk), which is 1460 ± 200 Ma, for crater 2, at the local stratigraphic boundary of Aeolis Mons and Murray formation (Figure 3, Le Deit *et al.*, 2013). Heterogeneity manifolds are shown in Figure 7, whereas graphics for parameters calculation is the same as on Figure 2. The age was calculated using the formula $= e^{\ln \bar{h}} \cdot e^{\Delta x}$ and expressed in million of years (Ma). See also discussions on the Subsection Accuracy of age estimation.

Impact craters Fig.1	$\ln(\bar{h})$	Δy	α	β	Δx	Calculated Age (Ma)
1	15.73417	5.0473	7.87	82.13	0.6976	2129.65
2*	16.15228	4.9494	7.5680	82.432	0.6577	2869.78
3	14.82497	5.9565	9.4949	80.505	0.99625	2871.22

near the geologic contact between Aeolis Plain and Mons, and reveals a synchronous age with the radiometric that was measured *in situ* at Mojave (which encompasses the lithification stage including the diagenesis and mineral formation within rocks). The results also suggest that rock units that are sampled by the other two craters (at depths >30 m, Table 2) were deposited and lithified 1.3 billion years after the formation of primary rocks and minerals within northern Gale (Figure 3). As the depth of rocks sampled by craters increases, the ages of rocks gets older (see Discussions below).

4. DISCUSSIONS

The initial constraints of our age model refer to: (1) the existing locations of the MSL age measurements, (2) the location and altitudinal distribution of craters that sample into local stratigraphy of near horizontal strata (Figure 1). We assume that (3) craters form randomly in time and space and evolve to the present state, for which a scaled heterogeneity parameter can be calculated, (4) small craters sample to the depths of CRE penetration, where the maximum age exposures reflect the antiquity of deposition and lithification through the entire study area, (5) any large crater could form anytime, long before one billion years exposure of rocks at Mojave, and any small crater could form long after 0.078 billion years exposure at Cumberland, to give just two endpoint situations that have the same chance of being true, and (6) large craters sample deeper, exposing older rocks. Here we aim to address the following question: How to relate the depth of strata being exposed in an instant back in time to the depth of strata affected by the cosmic ray exposure.

Some nearby similar-size craters, indurated rocks or colluvial mantles do not retain craters at all, or retain very few. In fact, a survey on all craters on MSL exploration area and beyond shows that the heterogeneity of craters in terms of diameters

Table 2

Crater morphometrical characteristics (depth and diameter in m) and number of craters sampling to the depth of the cosmogenic nuclides. The heterogeneity parameter value is the resultant of the manifold construction based on the morphometry of craters, and reflects the actual state of craters evolution. (NBSCS = number of small craters superposed, Alt = Altitude of sampled deposits)

Impact craters Fig 1	crater depth (m)	crater diameter (m)	NBSCS	Alt (m)	Heterogeneity value ($\bar{h}$)
1	18	292	7	-4514	6811820.8
2	39	458	6	-4444	10347746.7
3	31	474	16	-4476	2744137.6

and evolution is not showing a trend relative to their depths or type of deposits they sample (Newsom *et al.*, 2015). Hence, the importance of measuring the actual state of craters evolution as an equifinality. This equifinality is encapsulated into the manifold construction, which adds and scales each crater's dimension relative to their size, thus reflecting clearer how the number, size and magnitude of each impact contributes together to the present state of the cratered surface (Figure 7); the shape of the manifolds is also an indication of how the cratering is different as expected from craters forming at different times and where also sampling of rocks is done at different depths (Table 2 and Figure 7). We used the oldest exposure age measured so far by MSL as our age calibration anchor (although other age anchors are possible), because it reflects the antiquity of the geologic deposition and lithification across the entire study area. Mojave is also located altitudinally at a higher elevation than Windjana and Cumberland, and most likely reflects older ages of rock units due to the dipping stratigraphy towards north (Williams *et al.*, 2018). It is more likely that the rocks are at least as old as ~ 1060 Ma throughout the entire area and thereafter the rocks were exposed due to the differential erosion that was sampled at 300 Ma or 78 Ma by MSL, like the exposed rocks and surfaces nearby the striated (eroded) units at Windjana or Cumberland. This 1060 Ma age anchor is constrained chronostratigraphically by another age anchor at Quella of 1460 Ma (Le Deit *et al.*, 2013). We do not disregard the possibility to use other age anchors like those at Cumberland and Windjana. A more recent age anchor would imply preservation of the small craters during a later stage of eolian resurfacing and eolian mantling that is extensive in the study area, and thus not reflecting the rock formation period. Also, an anchor age closer to exposure at Yellowstone (78 Ma) or Windjana (300 Ma) would render a model age of rocks at depths exceeding 15 m and up to 40 m that are younger than the exposure ages at Mojave or Quella (both are located 5 to 15 m below the local Stimson/Bradbury stratigraphic contact or to the Murray/Stimson contact in the Quella case respectively (Le Deit *et al.*, 2013), see below).

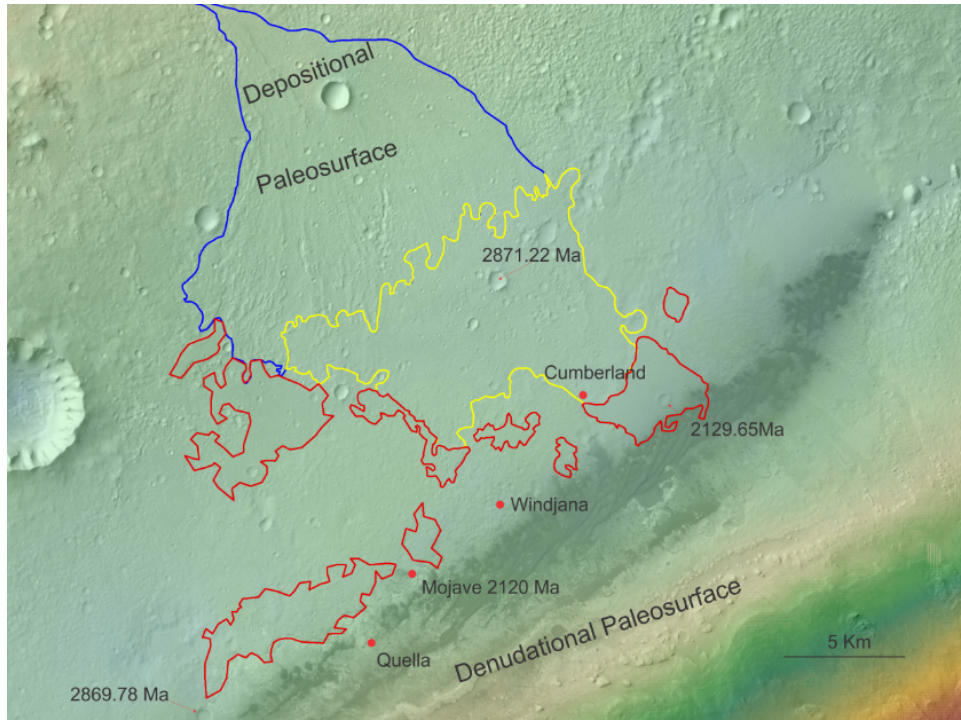


Fig. 3 – Benchmark ages for the geologic units that are derived from the $\bar{h}$ measurements for individual craters that are indicated here with red arrows. Secular deposition and denudation onto paleosurfaces are traced based on the age interpretation (see main text). Location of the MSL sampling sites where radiometric ages were measured in situ are shown in red dots. Major surface units perimeter are delineated with color as follows: AF (blue), BFU (yellow), CS (red). Background image is HRSC DEM overlaid on CTX imagery D02_027834_1748_XN_05S222W (Credit: NASA PDS Node).

In most cases, rocks are either exposed by denudation or sampled by craters, so the age anchor point can be equally related to the depth of craters and/or CRE penetration. We started with the crater 1 expecting that there is a significant age difference between the nearly horizontal sedimentary strata that are 60 meters one above the other (Figure 4, the topographic profile intersects crater 1 near point B).

We found that the calculated age of the crater sampling the CS unit exceeded with 9 Ma the formation age of a mineral jarosite at Mojave (Table 1). Our interpretation is that the proposed calibrated age could reflect the age of one lithification stage at this location (Edgett *et al.*, 2020), for the surface rocks that have been deposited and then scoured in a rapid succession of events before being sampled by the crater 1. The relatively young age for this rock unit that is sampled 15 m. in depth by crater 1, only offers partial clues on its formation age. The cratered surface (CS unit) is interpreted to be a resistant remnant of an erosional surface that retained more craters

than the less resistant units nearby, like the striated unit and hummocky unit that are emplaced towards the east and north (Anderson and Bell, 2010) (see the patchy disposal of CS unit, Figure 1, and also the lower altitude of the CS unit relative to the surrounding units, Figures 3 and 4).

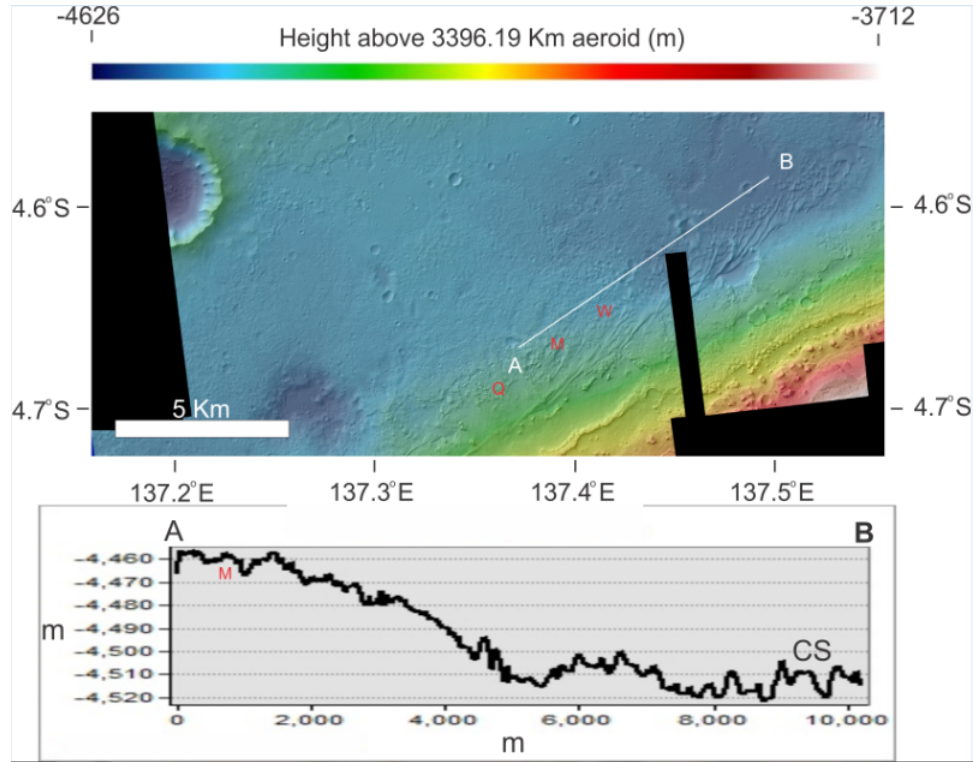


Fig. 4 – HiRISE DEM showing elevation distribution on MSL exploration area. A–B is the topographic profile. Cratered unit (CS) representing the smooth area near point B on the topographic profile is located in the proximity to Yellowknife Bay to the north-west and dune area to the south. Topographic profile showing 10 km distance between Mojave location (point A) and crater 1 location (point B), showing 60 m altitude difference between different rock units (see context in Figure 1). M indicates Mojave, W: Windjana and Q: Quella

Hence, crater 1 is a relatively fresh crater sampling into a rock unit that retains more craters than the surroundings. Nonetheless, our interpretation leans towards crater 1 sampling the unit of which age reflects the (partial) lithification stage that was described in the MSL area, where diagenetic characteristics of mineral emplacement occurred near 2120 Ma in concordance with the age of deposits sampled by crater 1 of 2129 Ma.

The CS unit ends abruptly towards the southern flank of Aeolis Plain (Fig-

Table 3

Crater 1 Craters morphometric characteristics used for manifold construction for crater 1; x, y and z in Tables 3 – 5 represent the location of the manifold chrono-morphologic upper surface in 3D space (Figure 5 top) that enables the calculation of the volume space and cental location of the datasets from which the heterogeneity parameter is calculated ($\bar{h} = V_{cm} \cdot Ed$, Căpitan, 2021)

Diam (km)	x_coord	y_coord	depth (m)	area (km ²)	x	y	z
0.014609	137.4853	-4.58752	0.133301	0.000168	4.131902	0.731414	0.233081
0.010313	137.4862	-4.58763	0.414551	8.35E-05	7.048755	3.00603	0.349235
0.006938	137.4843	-4.58907	0.418457	3.78E-05	9.011047	5.302078	0.401804
0.006995	137.4877	-4.5898	0.577149	3.84E-05	10.98946	8.46886	0.455241
0.005946	137.4854	-4.58789	0.647949	2.78E-05	12.67118	12.02412	0.493852
0.006166	137.4841	-4.58972	1.132813	2.99E-05	14.41513	18.23979	0.535374
0.302599	137.4862	-4.5899	14.90088	0.071916	100	100	100.5354

Table 4

Craters morphometric characteristics used for manifold construction for crater 2.

Diam (km)	x_coord	y_coord	depth (m)	area (km ²)	x	y	z
0.004235	137.267	-4.769	0.011	1.41E-05	0.833858	0.02675	0.008826
0.019589	137.271	-4.772	0.395	0.000301	4.690872	0.987306	0.197654
0.017249	137.263	-4.772	0.804	0.000234	8.087147	2.942464	0.344063
0.016012	137.268	-4.774	0.874	0.000201	11.23986	5.067847	0.470227
0.450795	137.267	-4.772	39.038	0.159606	100	100	100.4702

ure 1). At the same alignment to this morphologic and stratigraphic contacts, but several kilometers towards south-west, a relatively larger crater samples into surface rocks (crater 2). The crater is 80 m below Quella (Figure 5) but shares some erosional characteristics that are widely present in the lower Murray strata of Aeolis Mons. Crater 2 is also bigger than crater 1, and samples deeper into local geologic strata (Table 2). Our model age difference confirms the stratigraphic interpretation of Murray deposits being older than those of Bradbury. From the morphology of crater and visual inspection of imagery at HiRISE resolution (Figure 5), we can infer that a flow from Aeolis Planum partially occupies the northern rim of the crater, meaning that a stage of local sedimentation near crater 2 comes after an erosional stage of Aeolis Mons at this location. This type of resurfacing seems to be a trend within the entire area where the striated unit is formed on top of the CS unit, that is covered itself by the hummocky unit that extends further to both north and east near the Mojave and Cumberland further away from the known stratigraphic context revealed on MSL route, but inside Aeolis Plain.

Very few craters in the diameter range of crater 2 or below are preserved on Aeolis Mons (Newsom *et al.*, 2015; Daubar *et al.*, 2013) and specifically on this contact area towards Aeolis Palus. The prolonged erosion most likely striped away

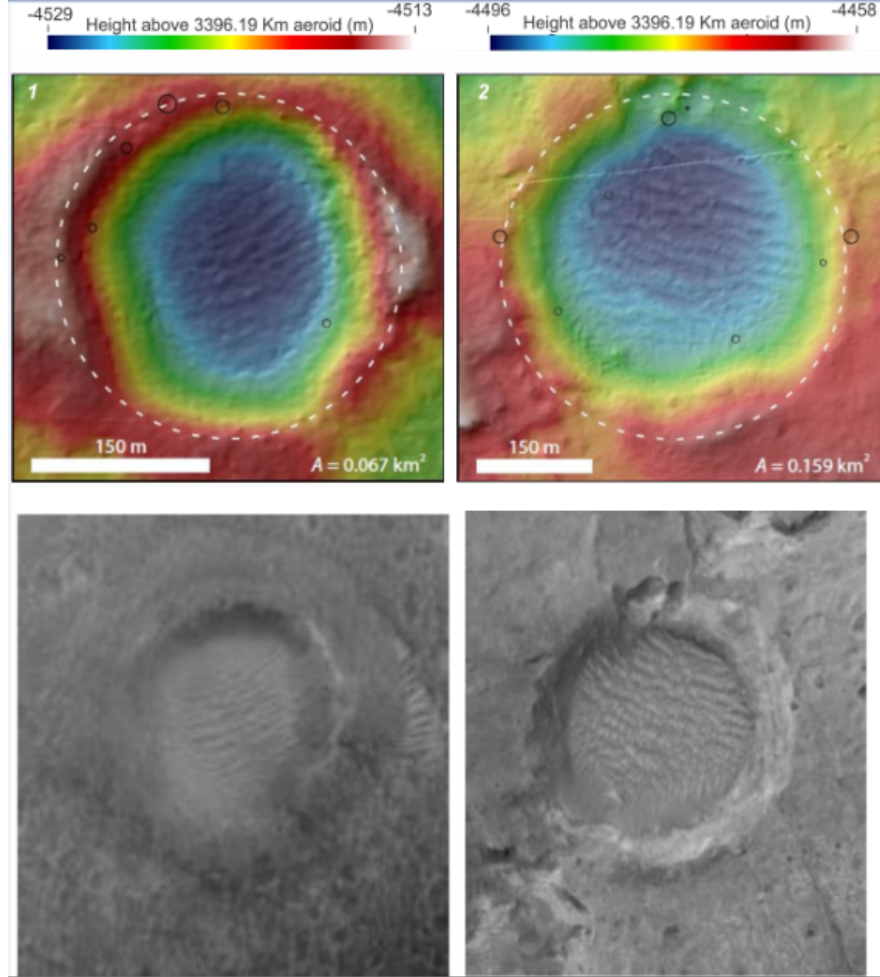


Fig. 5 – Top – DEM of craters 1 and 2 located at the boundary between Aeolis Plain and Mons (see Figure 1, main text, for context). Bottom HiRISE context images for the same craters (ESP.032436.1755 and ESP.043249.1750).

smaller craters that could have been formed here, and also some of the original surface deposits, as mentioned in literature (Grotzinger *et al.*, 2015; Smith, Gillespie, and Montgomery, 2008; Golombek *et al.*, 2014). Classical crater counting returns younger ages up to exposure ages within Yellowknife area because of the paucity of larger craters on a relatively small erosional window (Werner, 2019), whereas at the base of Aeolis Mons, if not over the entire MSL exploration area, only a resurfacing age estimate can be obtained using the CSFD dating technique.

Our proposed time difference between the two geologic units (*e.g.* the edge of

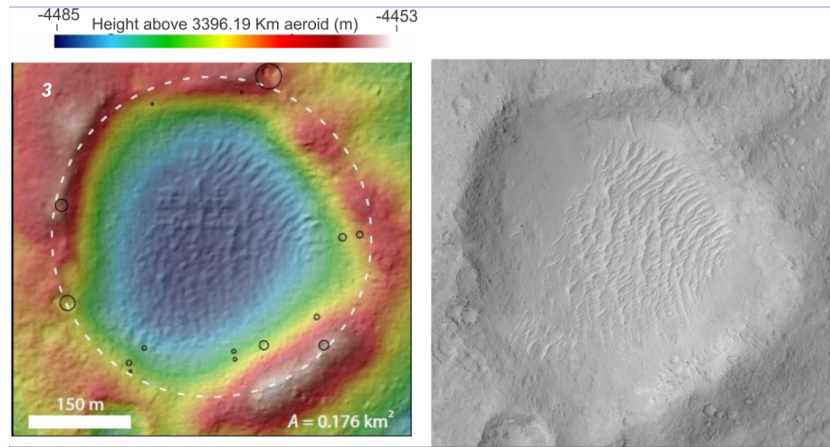


Fig. 6 – Left – DEM of crater 3 located at the within the lowest erosional depression on the Aeolis Plain (see Figure 1, main text, for context). Right HiRISE context images for the same craters ESP_018920_1755.

crater floor and lower Aeolis Mons) is calculated here to be in the range of 740 Ma. Given the overall stages of deposition and erosion that affected both stratigraphic contexts, we can infer that the age of deposits that are sampled by crater 2 could be seen as being formed during an early stage of sedimentation/lithification for the entire southern edge of the Aeolis Planum, as proposed in literature (Williams *et al.*, 2018; Edgett *et al.*, 2020), only far younger than the existing age in literature. Crater 2 samples strata at higher elevation than crater 1 (61 m), although its stratigraphic context and contact relative to the known stratigraphic column derived on MLS route remains unclear. Besides the altitudinal and stratigraphic context differences, crater 2 samples twice as deep as crater 1 (Table 2), and reveals an older model age as expected.

We next moved towards the front of the Peace Valis alluvial fan where a crater sampled into deposits mapped as the bedded fractured unit (Anderson and Bell, 2010). We used here the age anchor of Mojave since it samples into Aeolis plains stratigraphic context. This crater retains three times more craters than the craters located at the contact zone, and dig 8 m less than crater 2 and almost twice as deep as crater 1 (Table 2 and Figure 6). Nonetheless, despite being heavily eroded and retaining more craters, it has the same model age for the sampled deposits as those sampled by crater 2. This synchronicity of ages is remarkable, never being described so far in the dating literature, and implies the existence of a stage of local rock formation or a resurfacing stage in this area of Aeolis Planum.

None of the craters analyzed so far samples into a pristine depositional surface like a volcanic unit, but rather into diachronic surfaces and different stratigraphic contexts, hence the importance of correlations with the existing ground-truth ages.

Table 5

Craters morphometric characteristics used for manifold construction for crater 3

Diam (km)	x_coord	y_coord	depth (m)	area (km ²)	x	y	z
0.006098	137.41	-4.54	0.219	2.92E-05	0.925448	0.450265	0.016579
0.007031	137.413	-4.54	0.261	3.88E-05	1.992491	0.986883	0.038619
0.005916	137.411	-4.534	0.331	2.75E-05	2.890318	1.667421	0.054224
0.01593	137.415	-4.54	0.388	0.000199	5.307896	2.465151	0.167363
0.006275	137.413	-4.54	0.392	3.09E-05	6.260206	3.271105	0.184919
0.007714	137.41	-4.54	0.444	4.67E-05	7.430903	4.183971	0.211449
0.01001	137.416	-4.537	0.525	7.87E-05	8.950046	5.263374	0.256123
0.00624	137.413	-4.533	0.599	3.06E-05	9.897044	6.494922	0.273483
0.010686	137.415	-4.537	0.62	8.97E-05	11.51878	7.769645	0.324394
0.008471	137.41	-4.54	0.632	5.64E-05	12.80436	9.069041	0.356387
0.017859	137.408	-4.536	0.654	0.00025	15.51469	10.41367	0.498587
0.008997	137.415	-4.539	1.57	6.36E-05	16.8801	13.6416	0.534676
0.021177	137.408	-4.539	2.426	0.000352	20.09397	18.62947	0.734622
0.014687	137.413	-4.54	2.615	0.000169	22.32291	24.00592	0.830794
0.038237	137.413	-4.533	6.37	0.001148	28.12585	37.10268	1.48265
0.473596	137.412	-4.537	30.592	0.176159	100	100	101.4827

Likewise, the importance of model age concordance between craters 2 and 3.

Within most of the Aeolis Planum, most craters are smaller and heavily eroded, resembling that of crater 3. A density–diameter calibrated model age has been proposed using small craters near Cumberland, which could be applicable to very recent geologic episodes (78 Ma CRE), but the study did not extend the analysis outside Yellowknife where larger craters are present (Werner, 2019). This situation shows the complexity of cratering analysis at this scale of study, but nonetheless does not diminish the effort of the current method in deciphering the ages of surface deposits regardless of the how deep craters sample in depth, or their number and evolution differences, especially when confronted to such differences in rock formation and resurfacing history. This model age synchronicity between crater 2 and 3 raises the possibility that craters that form at two different times sample into a denudational paleo-landform that was put in place near 2870 Ma (Figure 3).

Such denudation context raise the possibility, although unlikely, that calibration to be made on younger exposure ages. For example, calibrating crater 1 age to the exposure age at Cumberland would render the following parameters: $\Delta y = 5.0473$, $\alpha = 9.161$, $\beta = 80.83$, $\Delta x = 0.81396$, and a model age of rock unit sampled by crater 1 of 176 Ma. This is unlikely since exposure on nearby Windjana at few meters higher in altitude reveals an exposure age of 300 Ma, thus older than the model age of the lower deposits of CS rock unit. Same would happen if we calibrate crater 1 age with the Windjana exposure age (300 Ma), rendering the same younger model age relative to the even higher location of Mojave and its older exposure age.

Therefore keeping the Mojave CRE anchor for our age calibration efforts for locations into Aeolis Palus seems the best approach. An example of the possible age calibration is performed for the crater that retains a large number of smaller craters inside its fresh crater unit. This crater looks fresh and has been used to demonstrate the depth of the alluvial mantling of the Peace Valis fan (Palucis *et al.*, 2016). If this major crater ($D > 700$ m) is calibrated to the distant Mojave CRE anchor age at 1060 Ma, for the crater depth of 61 m (Grant *et al.*, 2014), as shown in Figure 1) and 58 small craters superposing on it (HiRISE ESP_009650_1750), then, the resulted parameters would be: heterogeneity value $\bar{h} = 1261992.3$, $\Delta y = 6.7333$, $\alpha = 9.161$, $\beta = 79.058$, $\Delta x = 1.30175$, and thus a model age of rock unit sampled by this medium-size crater of 3896.26 Ma. This would put the result within the error range of the mineral formation age and possibly to the detrital deposition and rock formation at Cumberland and Windjana (Farley *et al.*, 2014; Vasconcelos *et al.*, 2016).

We cannot extend our calibration further away on the other craters that sample Aeolis Plain at this research stage because of large calibration uncertainties related in part to the unknown stratigraphy for deeper strata and the increasing depth of smaller craters sampling the biggest craters (see the example of the largest crater in Figure 1). It is still very likely that all craters that sample into the deposits on northern Aeolis could reveal similar old ages. This interpretation is the most plausible one since it is likely that a large portion of the materials that fill Gale crater interior form immediately after the moment of its formation. The mechanics of a 155 km crater excavation, and near instant rebound of materials during the initial stage (Grieve, Osinski, and Tornabene, 2014), put constraints on the existing interpretation that Aeolis Planum was covered by a 5 km thick sedimentary mound of Aeolis Mons near 3600 Ma, which afterwards has been presumably eroded away during 3600-3200 Ma (Grotzinger *et al.*, 2014; Williams *et al.*, 2018). Our maximum age model for the deposits that were put in place on Aeolis Plain at 61 m below the actual surface (and sampled by a relatively small crater when compared to other large craters nearby), make impossible such a scenario. This reference crater on top of Peace alluvial fan is also one of the most pristine craters in the study area (HiRISE ESP_009650_1750), but retains more small-size craters (meters in diameter) than any other surveyed craters, and thus most likely sampling long after any hypothetical exhumation period. Our interpretation that is derived from the age anchors at MSL location leans toward formation of the mound during Gale formation with no long term deposition and erosion of the 5 km thick sedimentary unit, as currently suggested. An in situ proof that sustains our interpretation is the lack of mineral phases similar to maskelynite that form under high pressure burial of rocks at the edge of the Aeolis Planum (Caswell and Milliken, 2017), hence lack of 5 km exhumation of the local stratigraphy. In addition, another study on the local mineralogy suggests a late Noachian global climate transition permissive of fluvial resurfacing and clay

formation, followed by long, dry, and cold weathering and predominant eolian resurfacing that formed most units that are explored by MSL (Liu, Michalski, and Zhou, 2021). On the other hand, CSFD age calibration suggest that surface units are at least 3600–3800 Ma, whereas we found evolved craters sampling upper rocks as old as only 2870 Ma. In this scenario, the current topography of Gale is much younger than expected. We also hypothesize a model age of rocks only 61 m below the current topographic surface as being 3890 Ma, which is incompatible with any possible existing resurfacing scenario in which 5 km thick sediments were exhumed. It is still less likely that burial and exhumation of Gale’s crater floor could have happened near 3896 Ma (if we consider the model age of deposits sampled by the largest crater), in a rapid sequence of events during different environmental conditions including a thicker atmosphere capable of sustaining sediment mobilisation at this volume (Kite *et al.*, 2013), because minerals or diaplectic glass components in rocks indicating the deep burial were not discovered by MSL.

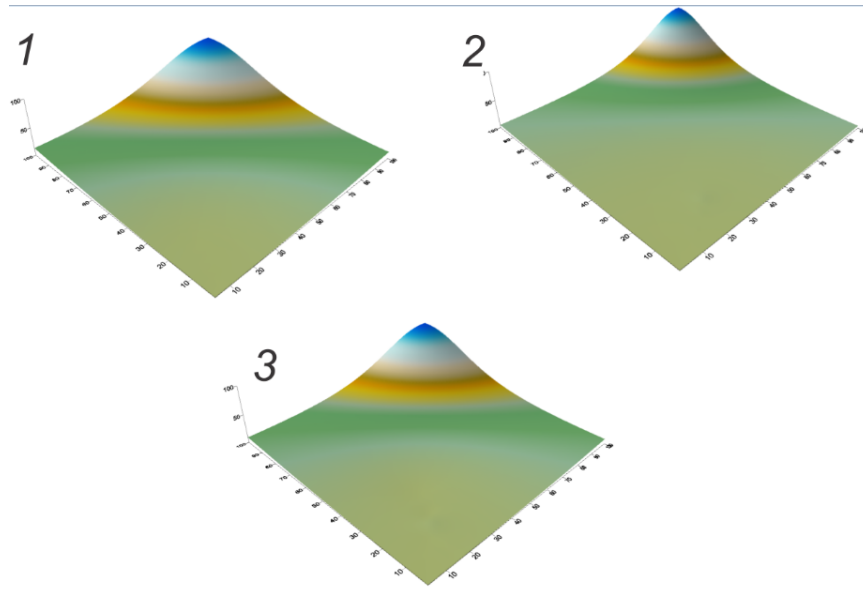


Fig. 7 – Manifold construct of the three craters in the study area. X and Y axes span from 0–100 percent, while z axes is the area occupied by the largest crater plus area of smaller craters, thus exceeding 100%.

A potential disadvantage of the new method is the difficulty to provide the error estimates due to paucity of in situ age calibration anchors, and to the existence of few available larger craters on which measurements on DEM are possible. Also, consider that this paper proposes for the first time using this type of morphometry

measurements in evaluating the age of rocks. Further data extraction that uses this method on other craters on Jezero or modeling on pristine volcanic units could improve the accuracy of current age estimations if ground-truth ages are returned. In the existing K/Ar ages for the Windjana and Mojave error margins overlap between 1790 and 1820 Ma for only two measurements (Le Deit *et al.*, 2013). Because there is no standard unit on which multiple age measurements can provide an accepted variation in our model age accuracy, 1 SD is calculated for the three units in the MSL exploration area, using the formula:

$$s = \frac{\sqrt{(x_i - \bar{x})^2}}{N - 1} \quad (2)$$

where x_i is the calculated age for each surface unit, $\bar{x}$ is the mean and $N = 3$ is the number of craters. A standard error is reflected by the standard deviation 1SD on our measurements, and provides an error of + or – 302.5 Ma at two degrees of freedom. Statistics can be used if we are sure that the K–Ar age measured by MSL is the true age of deposits and can be used as mean age over a larger area. Our initial measurement is a snapshot of three individual ages and reflect 1SD uncertainty of the mean age.

For any period of rock emplacement we may never be able to document any age error from crater counting alone, since the size of craters and rate of cratering over any age constraints may not match the duration of any rock formation that includes deposition, lithification and erosion, and sometimes exhumation. Instead, here we find a correspondence between our model ages and both the ground-truth ages: (1) the age of a mineral formation during the process of lithification, and (2) the age of mineral formation inside detrital rocks that are coeval with the formation of Gale crater itself, thus a potential calibration that does not rely on crater accumulation modelling. Considering the hypothesis that the rock units in the area of MSL exploration had been formed or at least denudated to the local extent at the time of crater 1 emplacement on top of CS geologic unit (Le Deit *et al.*, 2013; Thomson *et al.*, 2011; Schieber *et al.*, 2022), a difference of 9 Ma between these two events is considered here as a minimum age error calibration. Another calibration is given by the synchronous age of rock units sampled by craters 2 and 3 near 2870 Ma which suggest a resurfacing at the base of Aeolis Mons before exposure the unit CS by differential erosion at crater 1 location. Besides the synchronicity between the two craters that are also calibrated using two different anchor ages, it is important to state that these craters sample deeper the rocks than the exposure by local denudation documented by MSL. If the maximum exposure age is extrapolated to larger areas, the age deposits sampled by the major crater on top of Peace Valis can be seen as the minimum age of rock formation at depths of 61 m for the regional larger-scale Aeolis Planum unit (Farley *et al.*, 2014), and a possible maximum age anchor for Aeolis plain unit

(Figure 3).

Another component of the error in age measurements is given by the systematic error plotting. The systematic error plotting can be related to the accuracy of our measurements that is within the position of the crater rim relative to the size of the crater, within one pixel distance (Figures 5 and 6). For example, at HiRISE resolution, for a 20 m wide crater, the error between the center of pixel and position of the rim where crater extraction is performed is ± 60 cm, or 3 percent, whereas the extraction error decreases as the size of crater increases to several hundred meters. Other measurements on nearby area would increase the accuracy of age estimation and reduce the random uncertainty, which we foresee in further studies. Finally, another potential complication for age calculation model is related to the effects of secondary cratering that is observed on CSFD age calibration. As secondaries will continue to evolve just as will primaries, the fact that we include the post-formation evolution/degradation should reduce the influence of unidentified secondaries. In addition, MSL is not located in vicinity of any known recent impact craters of which rays or fields of secondaries would modify the results significantly (Newsom *et al.*, 2015).

5. CONCLUSIONS

This work presents for the first time a method that relates the ground-truth ages with sampling depths using the craters heterogeneity measurements. For craters formed near MSL exploration area we propose an age calibration model and a mathematical construct that reflect a link between the craters formation mechanisms and the depth of penetration into existing rocks. We link the ages of the upper deposits sampled by CRE penetration to ages of deeper deposits that are sampled by the deepest and the largest three craters that we surveyed. We found concordant and near-synchronous ages for deposits that are several kilometers away of each other. Most likely the protolith for the Kimberley and Cumberland sedimentary rocks have similar formation ages as elsewhere to the north near Peace Valis (Palucis *et al.*, 2016), and to those near Windjana and Mojave, assuming near-similar formation conditions as revealed by the existing stratigraphic columns (Grotzinger *et al.*, 2014) that extend across several kilometers explored by MSL. Local stratigraphy that was explored by MSL shows inter-bedded authigenic and detrital materials that were deposited and lithified, and loose materials inside smaller craters or the colluvial slopes. Orbital survey of Aeolis Plain inside Gale does not suggest large differences for the geology of the near-horizontal strata, which was confirmed also by MAHLI camera onboard of Curiosity rover (Grotzinger *et al.*, 2015).

All model ages are here calibrated using the maximum age anchors measured

so far by MSL. We explored here the hypothesis that an age anchor related to the sampling into upper few decimeters of surface rocks can be extrapolated (using the heterogeneity measurements) to older and deeper deposits that are sampled by larger craters. We use a mathematical construct and derive a concordant age with another *in situ* age at Mojave that describes a diagenetic formation of jarosite. If other available age anchors had been used, it would most likely be reflected as a late erosional stage near 100 to 300 Ma (Figure 1). Being diachronic surface units *de facto*, the local units like Windjana or Cumberland show the same erosional characteristics as those at Mojave, and are mixed with other units like the more resistant conglomerates. There may be also other surfaces that “look” older than Mojave considering their local physiography. If an older age anchor would have been available, most likely we had calculated an older age model for our three locations. Nonetheless, we used here the oldest exposure ages available for a local stratigraphic context (at Aeolis Plain/Aeolis Mons contact) and explore several locations sampled by larger craters to derive their ages.

We found concordant ages of the local rock units, even if only 3 craters are analyzed and one was given as an extended reference. We furthermore described here for the first time a synchronous age between two locations several kilometers away, and in different stratigraphic contexts, with rocks being sampled by craters that are so different in any possible way (*e.g.* morphometry, evolution characteristics, number of smaller superposed craters to state just a few). We also state here that our calibrated ages in the larger denudation context near MSL could represent resurfacing ages. In fact both ages we used are “sampling” ages by both cosmonuclide and craters. Nonetheless, on top of Peace Valis a crater sample deeper through a depositional surface, and may indicate a truth formation age. The extent of cratering heterogeneity method that is presented here is in fact an application of the dating method to the local stratigraphy; it is expected that multiple and deeper sampling will describe the true age of rock units over extended areas, as advocated by (Căpitan, 2021).

Regarding the accuracy of age estimation that we propose here, we found a smaller error range than the existent CRE error range for only three cases, due to the synchronicity of two model ages on rocks sampled by craters 2 and 3. Further work is needed to extend the method to other nearby craters.

We do not disregard the other younger ground-truth ages measured on Cumberland, Windjana and Mojave units, and further are aware of the limitations of the CRE ages for less than ~ 2 Ga, (Cohen *et al.*, 2019) (which add other constraints in age estimates for K-rich rocks), but favor the oldest measured age as a calibration anchor, and as an indication of the antiquity of exposure in the study area.

The current paper model ages are different than any existing crater counting-based model ages in literature in the sense that it proposes a different age calibration technique for the sequence of rock formation at Gale. As craters sample deeper, the

model ages for rocks are older than the ages proposed by the existing interpretation, favouring an early stage of rock formation near the mineral formation ages at Cumberland and Windjana. The model age reaches 3890 Ma, if we consider an age calibration for a large crater sampling on top of Peace Valis fan to depths of 61 m. If we consider only the anchor ages for the locations nearby the MSL measurements, our interpretation suggests concordant early formation of the major physiographic unit of Aeolis Planum near 2870 Ma, followed by a prolonged and possibly reduced in intensity resurfacing that is synchronous with a lithification stage 2120 Ma (including the cycles of sedimentation as proposed in literature, (Edgett *et al.*, 2020), with the protolith mobilisation and formation of the lithic units from 2129 Ma to present.

Finally, the present study shows that not necessarily the diameter nor the number of craters matter most in calculating an age of a geologic unit, but instead how the heterogeneity of craters morphometry contributes to reflecting the age of a sampled geologic unit. Most likely all of these larger craters formed at different times (we do not know when any crater forms near MSL exploration area), but the age calibration method that we propose suggests concordant and synchronous ages with the radiometric ground-truth ages. Considering the unknown formation age of craters and their morphometric heterogeneity, we show that despite the differences in cratering, the resultant heterogeneity parameter describes concordant ages for at least two locations, and a synchronous age with a mineral formation age near Mojave.

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