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Boulder abundances and size-frequency distributions on Oxia Planum-Mars: Scientific implications for the 2020 ESA ExoMars rover

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Abstract--

This paper presents the abundances and the size-frequency distributions (SFD) of boulders identified on a sector of the **prime** landing site for the ExoMars 2020 rover, in Oxia Planum region. By means of a HiRISE image, boulders ≥ 1.75 m **across** have been identified and subdivided according to the two main Oxia Planum geological units: the Noachian clay-rich formation (Nc), and the Amazonian volcanic deposit (Av).

- 19 The spatial density of boulders ≥ 1.75 m over the entire study area is $6.75 \times 10^{-4}/\text{m}^2$, with a size-
- frequency that is best fit both with power-law and exponential-law curves with indices of -4.9+0.1/-0.2 and -1.29 +0.04/-0.06 respectively. Significant differences were found by analysing separately the Av and Nc geological units. The data collected in the Av unit are well-fitted with a power-law curve with an index equal to -4.8 +/-0.2 and with an exponential-law curve with an index of -1.24 +0.05,-0.06, whilst in the Nc unit such indices are -5.5 +0.3/-0.4 and -1.70 +0.09/-0.12 (power-law and exponential-law curve, respectively).

The spatial density of boulders in the Av unit is 7.0 times **larger** than in the Nc one. This may be due primarily to the distinct mechanical properties of the two units that may result in a different production rate or preservation of the boulders. Secondly, the Av unit overlies the Nc unit, possibly resulting in more impacts and/or different weathering processes throughout the ages.

This study provides a quantitative evaluation of the abundances of boulders ≥ 1.75 m across on Oxia Planum: it is therefore a reference for the ExoMars 2020 mission, both during the landing phase and the rover traverse to specific areas of interest. The landing ellipse presents much higher abundances of boulders ≥ 1.75 m than all previous Martian rover landing areas. This is particularly evident when the rougher Av unit is taken into account. Contrarily, the Nc unit shows a much more comparable value, but still slightly higher, to the Mars Pathfinder landing site. We provide illustrative navigating scenarios for both the Nc and the Av units as well.

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38 **1.0 Introduction**

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More than 50 years ago, in 1965, the first unearthly boulders were revealed on the lunar surface thanks to the Ranger probe photographs (Kuiper et al., 1965). Afterwards, in 1977, both Viking spacecraft photographed Martian boulders (Mutch et al., 1977), suggesting that they might be ubiquitous on solid planetary surfaces. From that moment on, both the increasing number of different imaged bodies, as well as the increasing dataset resolutions, led to the possibility of studying the size-frequency distribution (SFD) of boulders present on the surface of a Solar system body.

Today, boulder SFD analysis is a widely accepted and useful tool to test and investigate the geomorphological processes that occurred, or are still occurring, on a planetary surface (e.g., McGetchin et al., 1973; Garvin et al. 1981; Craddock et al. 2000; Ward et al. 2005; Grant et al. 2006; Yingst et al. 2007, Golombeck et al. 2008, Yingst et al. 2010). This approach is not only used for planets, but there is also a vast literature documenting the SFD of boulders due to impact

- 52 cratering on the Martian satellites Phobos and Deimos (e.g., Lee et al., 1986), on asteroids like 243
- Ida, 433 Eros, 25143 Itokawa and 21 Lutetia (Geissler et al., 1996, Thomas et al., 2001, Michikami
- et al., 2008; Mazrouei et al. 2014, Kueppers et al., 2012), on the Moon (Bart and Melosh, 2010),
- and, more recently, on cometary nuclei, e.g. 67P/Churyumov-Gerasimenko and 103P/Hartley 2
 (Pajola et al., 2015, Pajola et al., 2016a).
- 57 For the specific case of Mars, multiple studies have related the derived SFD of boulders not only to
- 58 impact cratering (e.g., Melosh 1989), but also to erosive and depositional phenomena (e.g.,
- 59 Christensen P. R. 1986), as well as to aeolian processes (e.g., Hebrard et al. 2012). In addition,
- 60 thanks to the availability of in situ data obtained by landers and rovers, it has been demonstrated
- 61 that boulders are fundamental science targets that contain information both on the **morphological**
- processes on Mars, as presented at the Viking 1 (Chryse Planitia) and Viking 2 (Utopia Planitia)
 landing sites (Mutch et al., 1976a,b), and on the mineralogy and geochemistry of its surface, as
- 64 presented **at the** Pathfinder landing site (Morris et al., 2000), **at** Gusev crater by the rover Spirit
- (Hamilton & Ruff (2012)), at Meridiani Planum by Opportunity (Squyres et al., 2006), and at Gale
 crater by the Curiosity rover (Stolper et al., 2013).
- 67 In this context, the boulder abundances and the corresponding SFD are strictly related to the safety
- of a landing probe as well as to the roving (Golombek and Rapp, 1997; Golombek et al., 2003a,b,
- 69 2008, 2012, Pajola 2015b,c). Indeed, this aspect is one of the pivotal engineering constraints in a
- 70 landing site selection process (see, e.g., the call for Landing Site selection for the ExoMars rover:
- 71 <u>http://exploration.esa.int/mars/53458-exomars-2018-landing-site-selection-users-manual/</u>
- 72 Reference: EXM-SCI-LSS-ESA/IKI-003).
- To date, analysis of the boulders on the surface of Mars has used the images obtained by the High
 Resolution Imaging Science Experiment, HiRISE, which achieves a resolution of 0.25 m/pixel
 (McEwen et al., 2007). The identification of the boulders can be made both manually or by using
- automated algorithms (Golombek et al., 2008). In the first case, the analysis is particularly time
 consuming, therefore the investigated area is often smaller than the one that can be considered when
- an automatic routine is used. On the contrary, the automatic detection generally allows the collection of a large amount of data, but a manual validation is always required in order to avoid
- biased analyses (e.g. Cheng et al., 2001; Huertas, et al., 2006; Matthies et al., 2007, Golombek et
 al., 2008, Aboudan et al., 2014).
- 82 In this paper an analysis of the boulder abundances and their SFD is presented. The study area is 83 located inside the landing ellipse of the primary candidate for the ExoMars 2020 mission, namely 84 "Oxia Planum" (http://exploration.esa.int/mars/56686-landing-site-recommended-for-exomars-85 2018/). This area lies between the southern highlands of Arabia Terra and the northern plains of 86 Chryse Planitia (Fig. 1). The analysis focuses on boulders that have been manually identified in a 87 HiRISE image and then grouped on the basis of homogeneous geological units. Their SFD, as well 88 as the densities per m^2 and the corresponding power-law and exponential-law indices are presented 89 (in a log-log plot where the v axis is the cumulative number of boulder per m^2 and the x axis is 90 boulder size expressed in meters, the power-law index is the slope value of the regression line 91 that fits the SFD of the boulders, while the exponential-law indices are the multiplying factor
- 92 and the exponent of the exponential curve fitting the data). Finally, the implications for safety
- 93 and risks as well as the navigability of this area for the ExoMars 2020 mission are discussed.



Fig. 1. (a) MOLA context map showing the location of the Oxia Planum region (black rectangle) and the landing ellipse for the ExoMars 2020 mission. The primary landing ellipse (light blue) is 104 × 19 km wide, is oriented with an azimuth angle of 97°30' and its center is located at -24°30'59"E and 18°15'9"N. (b) CTX DTM located at the center of the ExoMars landing ellipse (light blue) with a spatial scale of 22 m/pixel. (c) HiRISE DTM covering the center of the Oxia Planum proposed landing ellipse. The spatial scale is 1 m/pixel. The red circle indicated by a red arrow is the study area where the boulder identification was performed. In (b) and (c) the green dot represents the center of the proposed landing ellipse.

2.0 Material and Methods

5 2.1 Imaging

The analysis of the Oxia Planum surface was performed by importing into the ArcGIS environment the HiRISE PSP_009880_1985_RED equirectangular map-projected image downloaded from the HiRISE image repository (http://www.uahirise.org). This image covers the center of the landing ellipse of the primary candidate for the ExoMars 2020 mission (Fig. 1, Quantin et al., 2015) with a swath that is 18.6 km long and 6.1 km wide; it is centered at 18.2°N and -24.5°E and was taken during MRO orbit #9880 with a phase angle of 55.77°, an emission angle of 7.8°, and a solar incidence angle of 48°, with the Sun 42° above the horizon. This image was taken at a distance of 285.3 km from the target surface, with an original scale range of 28.5 cm/pixel (with 1×1 binning); therefore, as stated in the HiRISE repository site for this image, objects larger than **85** cm across are here resolved. The resulting map projected scale is 0.25 m/pixel.

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118 2.2 High-resolution stereo DTM generation and validation119

Digital Terrain Models (DTMs) of the study area were produced in order to **allow** detailed characterization of the differences in elevation **within** our study area. In addition, such DTMs were used to investigate the different geological units of the area as well as to prepare the slope map of the area.

We chose a multi-scale approach in order to have an overall estimate of the Oxia region topography and a more detailed one **at** the center of the Oxia Planum landing site. Since **the resolution of** MOLA MEGDR topography (~463 m, Smith et al., 2001) is insufficient for our purposes, we used stereo DTMs derived both from CTX and HiRISE images. For this purpose, we selected a pair of the best overlapping CTX (~6 m/pixel, see Table 1) images and the single available HiRISE stereo pair (PSP_009735_1985_RED, PSP_009880_1985_RED).

All DTMs were produced and validated with the HRSC DTM (100 m/pixel) and the MOLA spheroid through the Ames Stereo Pipeline software (Moratto et al., 2010). All images were preprocessed with ISIS3 software (Integrated Software for Imagers and Spectrometers, Torson and Becker, 1997). CTX raw images underwent pre-processing involving attachment of SPICE kernels for camera pointing, radiometric calibration and destriping and projection. In addition, the HiRISE raw EDR data (experiment data records) were mosaicked, calibrated and de-jittered.

- The most important step before stereo matching was the bundle adjustment, required to obtain a validated DTM suitable for scientific analysis. This technique corrects the biases potentially affecting the DTM generated by erroneous pointing during acquisition of images that could result in altered surface features and inconsistency of the slopes. Bundle adjustment iteratively adjusts the position of the observer until the shift of the retro-projection of the pixels constituting the surface is minimized (Moratto et al., 2010).
- After the generation of the 3D point cloud created by the stereo matching, the pc align tool was 142 used to match the obtained point clouds with a reference-fixed one, in our case a HRSC DTM 143 144 (Table 1). This tool aligns and minimizes the shift in height of the obtained point cloud and its 145 possible displacement. In addition, it deletes the points that are too far from the reference point cloud and are not properly matching, degrading the overall accuracy (Moratto et al., 2010). We 146 147 adopted the H3059 0000 DT4.IMG HRSC DT4 as a reference for the alignment, because of its 148 height calibration on the Martian spheroid. The point cloud was then used to create a DTM according to the techniques described in Moratto et al., (2010), using a 4x post spacing of the input 149 150 image ground scale for CTX (5.6 m/pixel) and HiRISE (0.25 cm/pixel), resulting in an improved matching reliability (Moratto et al., 2010). We obtained DTMs of 22 m and 1 m post-spacing for 151 152 CTX and HiRISE respectively. The DTMs that were produced have an absolute height 153 referred to the MOLA geoid (Fig. 1) and the vertical precision is estimated at ~4 m for CTX 154 and ~0.4 m for HiRISE computed with the PILOT stereo matching tool (Bailen et al., 2015; Becker et al., 2015). The original HiRISE orthoimage we used is PSP 009880 1985 RED and, 155 156 in this case, the pixel resolution was kept at 0.285 m/pixel to preserve the original information 157 at its best, while the CTX stereo pair bears a pixel resolution of 5.65 m/pixel (resolving objects 158 ~17 m across) then resampled at 6 m/pixel. Such topographic information, coupled with other 159 derived maps (e.g. the slope map, obtained with ArcGIS 3D analyst function), was used in our 160 analysis.

Table 1: The HiRISE and CTX stereo pairs used in this work to produce the high-resolution DTMs. The HRSC DT4 used for their alignment is also included.

Instrument	Stereo couple product IDs	Pixel Scale	Phase Angle	Convergence Angle
HiRISE	PSP_009735_1985_RED PSP_009880_1985_RED	0.285 m/pixel 0.285 m/pixel	55.8° 41.2°	16.2°
СТХ	P22_009735_1977_XN_17N024W B01_009880_1977_XN_17N024W	5.64 m/pixel 5.65 m/pixel	41.4° 55.9°	16.3°
HRSC DTM	H3059_0000_DT4.IMG	-	-	-

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Fig. 2: (a) Orthorectified HiRISE image (PSP_009880_1985_RED) showing the Oxia Planum study area with a spatial scale of 0.285 m/pixel. The white rectangle shows the location of Fig. 3. (b) Slope map computed in degrees (Burrough and McDonell, 1998) and derived using the HiRISE DTM presented in Fig. 1c that covers the same surface of (a). The slope map is calculated at 1 m length scale. In both images the green dot represents the center of the proposed landing ellipse and the red circle corresponds to the boulder counting area (as for Fig. 1). The yellow line in b shows the -2982 m elevation referred to in the text.

2.3 Boulder identification

Our primary intent is to evaluate the average boulder abundance and associated SFD in a sector of the ExoMars 2020 **prime** landing ellipse. To do so, we chose a circular study area (2 km radius red circle in Fig. 1c and Fig. 2) centered on the landing ellipse center, and we manually identified the boulders inside it. Moreover, this area, 12.57 km², has been selected because it includes the two main geological units which have been mapped in the Oxia Planum region (Quantin et al., 2015) (see Section 3.0 for a detailed description), thus allowing **for the possibility of obtaining** useful insights into their evolution.

184 A "boulder" is defined as "a positive relief detectable with the presence of an elongated shadow (if the phase angle is greater than 0°), and appearing detached from the ground where it stands" (Pajola 185 186 et al., 2015, 2016d). Following the official USGS size terms after Wentworth (1922), "boulders" 187 have diameters >0.25 m, whereas "cobbles" range between 0.25 and 0.064 m and "pebbles" sizes range between 0.064 and 0.002 m. Since the rocks we identify in this analysis are all bigger than 188 189 1.75 m, i.e. much more than the official USGS 0.25 m limit, we call them "boulders". We 190 recall that with the HiRISE images we are using, objects larger than 85 cm across are 191 resolved, as stated in the HiRISE repository site for this image. Scarps and bedrock ledges are 192 characterized by elongated and aligned shapes that cast shadows on the surface as well but with 193 contiguous, if not uninterrupted shapes that are different to those of the commonly isolated 194 **boulders** (see white ellipses in Fig. 3). Hills and mounds, on the contrary, present isolated shadows 195 similar to those of the boulders, but such features are morphologically emerging from the ground 196 itself (as also visible and measurable in the related DTM and orthoimage) instead of appearing 197 detached from the ground (white boxes in Fig. 3). Following these guidelines, in this work we can 198 define all the identified features as "boulders".

Following Golombeck et al. (2003a, 2008), the detection of the boulders was based on the presence of their associated shadows. In particular, the boulders are approximated by circles centered at the estimated boulder position based on the shadow (see Fig. 3a and 3b). Their
diameter extends up to the terminator and partially overlap the shadows. The location of each
boulder, its diameter, and area are recorded. Fig. 3c and d shows the results of our boulder
identification methodology applied on a test area. We used ArcGis 10.4 software for the
identification and mapping.

206 We here underline that despite the common use of a circular shape for the considered boulders, we 207 do not mean that the mechanisms we propose for the boulder formation and evolution have to be 208 equant. We are aware that boulders can have elongated shapes, but we are focusing on their 209 maximum dimension distribution, as done in several other works not involving the boulders' 210 morphometry, e.g. Golombek et al., 2003; Michikami et al., 2008, Kueppers et al., 2012. By 211 knowing the pixel scale of the image, the boulders' diameters and the corresponding areas where they are located were then derived. The resolution of the HiRISE images allows the detection of 212 features down to 0.75 m in diameter (3 pixels sampling rule, Nyquist 1928). Nonetheless, it is not 213 214 uncommon that more than 3 pixels, e.g. 4-7 pixels, are considered as a lower boundary to provide a meaningful size-frequency statistic (Mazrouei et al., 2014; Pajola et al., 2015). Indeed, in this way, 215 216 the likelihood of boulder misidentifications is minimized. Moreover, according to previous studies 217 (e.g. Golombek et al., 2008), the smallest measurable boulder using shadows in HiRISE images is 218 typically ~1.5 m across.

The HiRISE image we used was **obtained at** a phase angle of ~56°, hence the presence of elongated shadows on the surface provided the possibility of identifying even smaller boulders (2 pixels, i.e. 0.5 m in size, see **Table 2**). However, we considered the minimum diameter to be 1.75 m, as the SFD below this value starts to roll over, indicating that the sampling might not be complete (see section 4 for a detailed discussion).





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Fig. 3: Methodology used to identify two boulders located on the surface of Mars. A) Close-up of a set of boulders. The casted shadows are indicated with white arrows. B) Same as A, but with the fitted circles located at the terminators of the two boulders and partially overlapping the shadows. C) Subframe of the HiRISE image used in our analysis. The white arrows indicate the direction of the sunlight. The white ellipses indicate scarps and ledges of different sizes, while the white squares show hills/mounds with different dimensions. D) The detected boulders ≥ 1.75 m, grouped in size-categories (m).

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233 **3.0 Geological analysis**

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235 3.1 Geological mapping236

A geological analysis based on bibliographic data, as well as on geomorphological observations,
has been carried out over the study area. The geologic units were mapped on the basis of surface

texture, relief, and albedo. We made use of both high-resolution imaging (i.e. orthorectified 239 HiRISE image), coupled with DTM elevations (MOLA, CTX and HiRISE-based, Fig. 1) and the 240 241 slope map **derived from** the HiRISE DTM at 1 m length scale (Fig. 2). Mineralogical analyses have 242 been performed in the Oxia Planum region (e.g. Carter et al., 2015a,b, 2016, Quantin et al., 2016) and, even if these studies did not focus on our studied area, such data have been used to strengthen 243 244 our interpretation. The resulting geological map, presented in Fig. 4, follows the criteria routinely 245 adopted for planetary geological mapping (Hansen, 2000). This section is intended to constitute a basis for the boulder analysis and interpretation. Any speculation on geological processes that lead 246 to the deposition of the identified units has been avoided, since such formation processes are 247 discussed in detail in a companion paper (Quantin et al., in preparation) focusing on the entire Oxia 248 249 Planum as the next ExoMars 2020 landing site.





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Three geological units have been identified (Fig. 4), and are here listed in stratigraphic order from the oldest to youngest, together with their prominent characteristics:

Noachian clay-rich formation (Nc): this light-toned unit constitutes the majority of the study area, outcropping within the eastern sector of the study area and in large parts of the Oxia Planum region (Carter et al., 2015a, 2016; Ciarletti et al., 2015; Loizeau et al., 2015a; Quantin et al., 2015; Quantin et al., 2016). This unit presents a smooth texture at the HiRISE resolution (Fig. 5, detail 1) and is characterized by generally gentle slopes (Fig. 2),

excepting the flanks of the craters. It can be subdivided morphologically into two main
 homogeneous regions: the eastern plateau and the western lowlands. The plateau is located
 almost entirely above -2982 m MOLA and is connected to the low-lying western part by a
 gentle (about 7-14° inclined) slope. As can be appreciated in Fig. 2b, the lowlands are
 remarkably smoother than the plateau, with slope values never exceeding 7°.

266 Several patches of wind-blown deposits can be found on the surface of this unit, in particular 267 in the lowlands (see Fig. 5b, detail 5, Fig. 6 and paragraph 3.3) and a continuous belt of 268 scree material can be found next to the sharp scarp (Fig. 5b, detail 6) that bounds this unit to 269 the west. Multiple studies (e.g. Carter et al., 2015a,b, 2016; Quantin et al., 2016) point out the presence of hydrated minerals in this unit, with a widespread occurrence of Mg/Fe 270 271 phyllosilicates, consistent with either vermiculites or smectite-bearing mixed-layered clays. This unit has been found to date back to the Middle Noachian (3.9-4 Ga; Quantin et al., 272 273 2016) and has experienced various resurfacing events that lead to a Late Amazonian 274 exposure age (~100 Ma; Quantin et al., 2016). 275

- 276 • Amazonian volcanic deposits (Av): this unit outcrops in the western sector of the study 277 area, next to the Nc unit, from which it is separated by an abrupt scarp (40° to 60° inclined 278 and 10 to 20 m high, see Fig. 1, 2b and 5b, detail 6) the base of which is at an elevation of 279 about -2982 m MOLA. The Av unit is remarkably darker than the Nc one, and presents an 280 extremely rugged surface at the HiRISE resolution. Sharp crests alternate to small 281 depressions (Fig. 5b, detail 2), visible both in the images and in the slope map (Fig. 2). 282 Compared to the previous unit, a larger quantity of craters and a much higher number of 283 boulders is present (boulder density is more than 7.0 times higher, see section 4 for details). 284 No mineralogical signatures of hydrated minerals have been found here. Indeed, this unit is interpreted to be basaltic lava flows, due to the presence of morphologies related to 285 286 effusive volcanism and to the absence of a hydration signature (Quantin et al., 2016). It locally covers the underlying stratigraphic succession, protecting it from the effects of 287 erosive processes and meteor impacts. Previous studies date the deposition of this unit to the 288 Early Amazonian era (i.e. 2.6 Ga; Quantin et al., 2015, Quantin et al., 2016) and suggest that 289 290 it has been remarkably eroded since its deposition. Given that this unit overlies the Nc one, 291 it is likely that thin patches of Av may still **be** present on top of the older unit. This is surely 292 the case for the isolated outcrop located south of the center of the study area, but may also 293 be the case for the darker areas scattered on the Nc unit (Fig. 5b, detail 4). However, since 294 the identification is **uncertain**, we prefer to include such areas in the older geological unit 295 (see Fig. 4). 296
- 297 ٠ Noachian-Amazonian mound (NAm): this is a geological inconsistency with respect to 298 the two main units presented above. It is a mound with high relief (about 50 m high) and 299 sharp scarps that connect it to the Nc unit. It appears to be dissected in the middle by a deep incision (Fig. 5, detail 3) with steep flanks. This geological element appears to be different 300 from the previous units and it has been distinguished from them, in order to avoid any bias 301 in the boulder analyses. Unfortunately, the flanks surrounding this outcrop are covered by 302 aeolian and scree deposits and it is not possible to assess if it lays on top of the Nc unit, thus 303 possibly being a remnant of the Av unit, isolated by erosional processes, or it belongs to a 304 305 stratigraphically lower (and older) geological unit.



307 308 Fig. 5: (a) HiRISE image of the study area with the location of the underlying close-up images (b) HiRISE close-ups; all 309 of them have been taken from the same image, at the same zoom (exception made for detail 5, which has a 2x zoom) 310 and with the same stretching conditions, in order to allow visual comparisons of both textures and color tones. 1: Nc 311 unit: the smooth texture of the terrain is easily perceivable, as well as its light tone; 2: Av unit: rugged textures of the 312 terrain and dark tone are distinctive characteristics of this unit; 3: NAm unit: the central fracture and almost vertical 313 flanks of this outcrop, surrounded by the Nc unit, are clearly visible in the close up; $\frac{4}{3}$: darker patches of rock in the Nc 314 unit, possibly constituting a thin layer of Av unit that survived the erosion; 5: 2x zoom image of aeolian ridges; it is 315 possible to note some boulders lying on these deposits; 6: small section on the sharp scarp that separate the Nc unit from 316 the Av one; it is here possible to notice a belt of mixed scree and aeolian sediments that accumulates at the foot of the 317 scarp (northern side, in this image). 318

319 2 Fine-grained material distribution

320 The accumulation of fine-grained (particles <0.25 m) material due to wind and/or gravity-321 related phenomena can potentially cover boulders, biasing the results. Fig. 6 shows the 322 distribution of all deposits that appear to be formed from such sediment. These deposits may 323 represent aeolian material, such as aeolian ridges (Fig. 5b, detail 5) or scree sediments that 324 accumulate at the base of the scarps (Fig. 5b, detail 6). However, since scarps are efficient obstacles 325 to wind flow, these latter deposits are probably mixed in origin. As can be seen in Figs. 2, 4, and 5, at the main boundary between the Av and Nc unit an almost continuous belt of such debris 326 327 fields is present.

- We identified deposits covering a total area of 1.59 km² (i.e. 12.65% of the total analyzed surface, and 14% and 9% of the Nc and Av units respectively) (Fig. 6). Despite the potential obscuring effect of these deposits, we were still able to identify boulders laying on them (Fig. 5b, detail 5). Therefore, we believe that our boulder identification is not significantly biased and a meaningful size-frequency distribution analysis can be computed.
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Fig. 6: Fine-grained material distribution over the study area (black areas).

339 4.0 SFD results

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341 **4.1 The entire study area**

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343 Over the entire study area (12.57 km²) we identified 27,625 boulders ≥ 0.50 m, 8489 of which 344 **are** ≥ 1.75 **m across**. The corresponding density of boulders ≥ 1.75 m per m² is 6.75×10^{-4} . Table 2 345 presents the statistics of the collected boulders, grouped in bins of 0.25 m, i.e. the HiRISE image 346 resolution.



348 349 Fig. 7: (a) Spatial distribution of all the identified boulders ≥ 1.75 m (green dots, detected on original HiRISE image 350 and then reprojected onto the orthorectified one) within the study area (12.57 km^2) . (b) Density map of boulders in 351 the study area. It is worth noting that the highest values are reached in the western sector, over the Av geological unit. 352 In the Nc unit the highest densities are found in the eastern side of a large crater, near the center of the study area. (c) 353 SFD of the identified boulders (bin size 0.25 m, Table 2). According to Michikami et al., 2008, vertical error bars 354 indicate the root of the cumulative number of counted boulders divided by the considered area. The data were fitted 355 356 with a linear regression (solid black line) and with an exponential curve (solid blue line) performed in the 1.75 -6.75 m interval (highlighted in grey). 357

Fig. 7a shows the spatial distribution of all the identified boulders ≥ 1.75 m overlaid and rectified on the HiRISE DTM, while Fig. 7b shows how the rock density varies across the studied area. Spatial densities (number of boulders per m²) have been calculated over the study area with a mobile circular cell (250 m radius) and subdivided into seven classes. The highest values are reached in the western sector, over the Av geological unit. In the Nc unit a peak in the density values is found in the eastern side of a large crater, near the center of the study area.

The cumulative boulder SFD per m² of the entire area is shown in Fig. 7c. Both the power-law and the exponential-law fitting curves used to interpolate the number of boulders per m² take into account those boulders within the 1.75 - 6.75 m diameter range. The power-law index derived from the total amount of boulders \geq 1.75 m is -4.9 +0.1/- 0.2 (Fig. 7c black line) with a coefficient of determination (R²) equal to 0.992. The fitting exponential curve has an exponent of -1.29 +0.04/- 0.06 and a R² value of 0.980 (Fig. 7c blue curve). These results suggest that in
 the selected range both power and exponential models provide good fits to the data.

372 As described above, for the statistical analysis we considered the smallest diameter to be 373 1.75 m across. Below this value, the power-law model overestimates the sizes while the exponential model underestimates them (regression lines are above/under the data, 374 375 respectively). As suggested in other studies (e.g. Heet et al 2009, Hebrard et al 2012), the 376 observed cumulative distribution flattens at sizes smaller than ~1.5 m due to the resolution 377 limit of the image. At that diameter size, the power-law model tends to overestimate the smaller diameter boulders, while the flattening of the exponential distributions allows a better 378 379 representation of the distributions of such boulders (Golombek et al 2008, Hebrard et al 2012). Following Michikami et al., (2008) and Pajola et al., (2015, 2016d), we do not consider 380 381 such boulders larger than 6.75 m in diameter, since the presence of the same cumulative 382 number in subsequent values is an indication of poor statistics. Such values, typically the bigger boulder sizes, should not be considered by the fit to avoid misinterpretations. In fact, 383 384 sizes greater than 6.75 m are slightly overestimated by the power-law model while clearly 385 underestimated by the exponential one.

386 387 These considerations apply to all size-frequency plots presented in this paper.

Table 2: Statistics of the identified boulders, grouped per bin (0.25 m wide). The grey rows show the size range of the boulders considered in the statistical analysis of Fig. 7.

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J	,	υ	

Bin*	Absolute	Cumulative	Cumulative
[m]	frequency	number**	number/m ²
0.50	1480	27625	2.20×10 ⁻³
0.75	3399	26145	2.08×10 ⁻³
1.00	5048	22746	1.81×10 ⁻³
1.25	4892	17698	1.41×10 ⁻³
1.50	4317	12806	1.02×10 ⁻³
1.75	2890	8489	6.75×10 ⁻⁴
2.00	1869	5599	4.45×10 ⁻⁴
2.25	1391	3730	2.97×10 ⁻⁴
2.50	796	2339	1.86×10 ⁻⁴
2.75	536	1543	1.23×10 ⁻⁴
3.00	303	1007	8.01×10 ⁻⁵
3.25	230	704	5.60×10 ⁻⁵
3.50	136	474	3.77×10 ⁻⁵
3.75	109	338	2.69×10 ⁻⁵
4.00	67	229	1.82×10 ⁻⁵
4.25	41	162	1.29×10 ⁻⁵
4.50	35	121	9.63×10 ⁻⁶
4.75	20	86	6.84×10 ⁻⁶
5.00	20	66	5.25×10 ⁻⁶
5.25	9	46	3.66×10 ⁻⁶
5.50	8	37	2.94×10 ⁻⁶
5.75	6	29	2.31×10 ⁻⁶
6.00	3	23	1.83×10 ⁻⁶
6.25	1	20	1.59×10 ⁻⁶
6.50	3	19	1.51×10 ⁻⁶
6.75	0	16	1.27×10 ⁻⁶
7.00	5	16	1.27×10 ⁻⁶
7.25	1	11	8.75×10 ⁻⁷
7.50	6	10	7.96×10 ⁻⁷
7.75	1	4	3.18×10^{-7}

8.00	2	3	2.39×10 ⁻⁷
8.25	0	1	7.96×10 ⁻⁸
8.50	0	1	7.96×10 ⁻⁸
8.75	0	1	7.96×10 ⁻⁸
9.00	1	1	7.96×10 ⁻⁸

* the column reports the lower limit of each bin; ** the cumulative number is intended as the number of boulders with dimension equal to or greater than the selected lower limit (i.e. first column).

394 4.2 Localized areas

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396 The **lithology** of single boulders could be inferred neither from visual examination nor 397 mineralogical data due to their limited dimensions. A transport origin should be considered as a 398 possible factor for boulder deposition, but the problem with this hypothesis is that the aeolian 399 transport is not admissible, since it requires an unrealistic amount of energy to move clasts such as 400 those considered in this study. A fluvial/glacial environment can be suggested, but the closest 401 fluvio-deltaic deposits identified so far in the Oxia Planum region are located more than 30 km to the south east of the study area, at the outlet of Cogoon Vallis (Quantin et al., 2016). When all such 402 403 aspects are taken into account, it is likely that the considered boulders are composed of the same 404 lithology as the geological unit that they overlie. Moreover, the analysis of terrestrial crater ejecta 405 suggests that large clasts derive from near surface regions, whilst the smaller ones originate from deeper levels (Kumar et al., 2014): therefore, by considering the size of the boulders involved in our 406 407 study (i.e. ≥ 1.75 m), we suggest that most of them come from the near surface, corroborating our *a*-408 priori assumption.

409 Following the geological analysis (Fig. 4), we grouped those boulders located on the Av and Nc 410 unit, to investigate if any differences in SFD are present between boulders belonging to different geological units. On the 3.29 km² Av unit, the cumulative number of boulders > 1.75 m across is 411 5881, with a density value of 1788 boulders/km², Table 3. Conversely, the cumulative number of 412 boulders ≥ 1.75 m across identified on the 8.97 km² Nc unit is 2285, with a density value of 413 2.55×10⁻⁴ boulders/m². In the Av unit, the fitting power-law curve has an index of -4.8 +/- 0.2 414 $(\mathbf{R}^2 = 0.996)$ (Fig. 8a black line), whereas the exponential-law curve shows an exponent of -1.24 415 +0.05/- 0.06 ($\mathbb{R}^2 = 0.981$) (Fig. 8a blue curve). The Nc unit (Fig. 8b), shows a power-law index 416 of -5.5 + 0.3/-0.4 (R² = 0.985) and an exponential model with an exponent of -1.70 + 0.09/-0.12417 418 $(\mathbf{R}^2 = 0.996).$

419 As for the entire studied area, the results show a good agreement between the power-420 law/exponential-law curves and the data within the fitting ranges. The power-law model again 421 overestimates the size of boulders both below and above the fitting ranges, in both units. The 422 exponential fit shows an underestimation of the diameters < 1.75 in the Av unit and a small 423 overestimation for the same sizes in the Nc unit. As previously observed (Fig. 4), the 424 distributions of the data tend to flatten at smaller boulder sizes (~1.5 m). Again, this is a result 425 of the resolution limit of the images used to derive the distributions (e.g. Heet et al 2009, 426 Hebrard et al 2012). As previously discussed, the exponential-law curve that is curved in a 427 log-log plot tends to better represent the flattening of the distribution at small sizes when 428 compared to the power-law fit.

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We point out that a large crater (diameter = 230 m) is located within the Nc unit (Fig. 8, black arrows), clearly surrounded by radial ejected boulders. This feature, remarkably larger than other craters in the study area, may have locally increased the density of boulders and, therefore, the mean Nc boulder density over larger sectors may be even smaller than that one obtained in our case. Consequently, the ratio between the boulder densities of the Av and the Nc unit may be even greater than the measured value of 7.0. Due to the high uncertainties and possible biases

- that would derive from a manual removal of boulders connected to this feature, we decided
- 437 not to exclude them.



438 Boulder Size (m)
439 Fig. 8: Uppermost panel: HiRISE DTM showing the spatial distribution of all boulders detected, grouped according to
440 the geologic units. Those located on the Av unit are shown in light-blue, whilst those on the Nc unit are shown in
441 purple. Black arrows in the top panel show the location of the crater referred to in the text. The cumulative SFDs for
442 both regions are presented in a) and b). The data were fitted with a linear regression (solid black line) and with
443 an exponential curve (solid blue curve) performed on data between 1.75 and 6.75 m on the Av unit and between
1.75 and 5.25 on the Nc unit (the fitting ranges are highlighted in grey) as shown in Fig. 7.

Table 3: Statistics of the identified boulders, grouped per bin (0.25 m wide) over the Av and the Nc units, respectively.

		Av Unit				Nc Unit	- L
Bin*	Absolute	Cumulative	Cumulative	Bin*	Absolute	Cumulative	Cumulative
[m]	frequency	number**	number/m ²	[m]	frequency	number**	number/m ²
0.50	1125	19347	5.88×10 ⁻³	0.50	353	7798	8.69×10 ⁻⁴
0.75	2297	18222	5.54×10 ⁻³	0.75	1088	7445	8.30×10 ⁻⁴
1.00	3420	15925	4.84×10 ⁻³	1.00	1599	6357	7.09×10 ⁻⁴
1.25	3529	12505	3.80×10 ⁻³	1.25	1310	4758	5.30×10 ⁻⁴
1.50	3095	8976	2.73×10 ⁻³	1.50	1163	3448	3.84×10 ⁻⁴
1.75	2001	5881	1.79×10 ⁻³	1.75	815	2285	2.55×10 ⁻⁴
2.00	1304	3880	1.18×10 ⁻³	2.00	494	1470	1.64×10 ⁻⁴
2.25	944	2576	7.83×10 ⁻⁴	2.25	395	976	1.09×10 ⁻⁴
2.50	571	1632	4.96×10 ⁻⁴	2.50	182	581	6.48×10 ⁻⁵
2.75	346	1061	3.23×10 ⁻⁴	2.75	165	399	4.45×10 ⁻⁵
3.00	216	715	2.17×10 ⁻⁴	3.00	71	234	2.61×10 ⁻⁵
3.25	154	499	1.52×10 ⁻⁴	3.25	56	163	1.82×10 ⁻⁵
3.50	92	345	1.05×10 ⁻⁴	3.50	40	107	1.19×10 ⁻⁵
3.75	75	253	7.69×10 ⁻⁵	3.75	26	67	7.47×10 ⁻⁶
4.00	48	178	5.41×10 ⁻⁵	4.00	15	41	4.57×10 ⁻⁶
4.25	30	130	3.95×10 ⁻⁵	4.25	8	26	2.90×10 ⁻⁶
4.50	30	100	3.04×10 ⁻⁵	4.50	4	18	2.01×10 ⁻⁶
4.75	17	70	2.13×10 ⁻⁵	4.75	3	14	1.56×10 ⁻⁶
5.00	15	53	1.61×10 ⁻⁵	5.00	5	11	1.23×10 ⁻⁶
5.25	7	38	1.16×10 ⁻⁵	5.25	2	6	6.69×10 ⁻⁷
5.50	5	31	9.42×10 ⁻⁶	5.50	2	4	4.46×10 ⁻⁷
5.75	6	26	7.90×10 ⁻⁶	5.75	0	2	2.23×10 ⁻⁷
6.00	3	20	6.08×10 ⁻⁶	6.00	0	2	2.23×10 ⁻⁷
6.25	1	17	5.17×10 ⁻⁶	6.25	0	2	2.23×10 ⁻⁷
6.50	3	16	4.86×10 ⁻⁶	6.50	0	2	2.23×10 ⁻⁷
6.75	0	13	3.95×10 ⁻⁶	6.75	0	2	2.23×10 ⁻⁷
7.00	4	13	3.95×10 ⁻⁶	7.00	1	2	2.23×10 ⁻⁷
7.25	0	9	2.74×10 ⁻⁶	7.25	0	1	1.12×10 ⁻⁷
7.50	6	9	2.74×10 ⁻⁶	7.50	0	1	1.12×10 ⁻⁷
7.75	1	3	9.12×10 ⁻⁷	7.75	0	1	1.12×10 ⁻⁷
8.00	2	2	6.08×10 ⁻⁷	8.00	0	1	1.12×10 ⁻⁷
	-	-		8.25	0	1	1.12×10 ⁻⁷
				8.50	0	1	1.12×10 ⁻⁷
				8.75	0	1	1.12×10 ⁻⁷
				9.00	1	1	1.12×10 ⁻⁷
					1	1	-

447 The grey rows show the size ranges of the boulders considered in the statistical analysis of Fig. 9.

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* the column reports the lower limit of each bin; ** the cumulative number is intended as the number of boulders with dimension equal to or greater than the selected lower limit (i.e. first column).

4.3 Sensitivity analysis

456 To provide information on the sensitivity of the presented results to the size of the detected 457 boulders, we performed a numerical simulation randomly changing the diameter of such 458 boulders within selected ranges. We adopted the same technique presented in **Baratti et al.**, 459 **2015** and **Pajola et al.**, **2017**. The experiment was separately performed for *(i)* the whole 460 sample of the detected boulders, *(ii)* for the boulders detected on the Av and *(iii)* for the 461 boulders detected on the Nc units. 462 As a first step, each detected diameter was independently perturbed by adding a value 463 extracted from uniform distributions in the ranges ± 0.125 , ± 0.25 and ± 0.50 m (i.e. 464 corresponding to half, one and two pixels of the used HiRISE image). Later, the boulder 465 diameters were binned using the same lower and upper bin limits reported in the first 466 columns of tables 2 and 3 (i.e. increasing step of 0.25 m). Finally, the SFDs' power-law and 467 exponential-law fits were recomputed in the same range of diameters previously adopted (i.e. 468 1.75-6.75 m for the whole area and the Av unit, and 1.75-5.25 m for the Nc unit).

469 In each case we performed 10^5 simulations. The experiment was performed in order to provide 470 information about the accuracy and the overall objectivity of the detected diameters and the results. 471 The maximum selected perturbation of two pixels is based on the assumption that in our 472 manual detection we consider unlikely an error of over- or underestimation greater than 2 473 pixels. Indeed, as suggested by Golombek et al. (2008), the accuracy in the manual detection of 474 boulders (in a MOC image) is within ±1 pixel. Thus, although this conclusion may be 475 questionable, we retain that our maximum adopted perturbation (i.e. ±2) is conservative. 476



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Fig. 9: Sensitivity analysis - box plot of **the power-law and exponential-law indices obtained** by varying the size of the identified boulders by ± 0.125 , ± 0.25 and ± 0.50 m (i.e. half, one and two pixels). The upper and lower hinges correspond to the 25th and 75th percentiles; the whiskers extend from the minimum to the maximum values.

The results obtained are presented in Fig. 9. Both fitting models (power-law and exponential-483 law) show for all units increased variability in the indices with an increasing range of the 484 485 selected perturbations. A higher sensitivity of the results is found for the boulders in the Nc unit, as we expected due to the smaller amount of boulders used for this unit (2285), 486 487 compared to the Av one (5581) and to the entire region (7866). Nonetheless, the Av unit shows 488 power-law and exponential-law indices that are always greater than the Nc one, with values 489 ranging between $-4.75 \div -5.00$ and $-1.22 \div -1.28$ compared to $-5.25 \div -5.75$ and $-1.6 \div -1.8$ for 490 the Nc unit (power-law and the exponential-law curves, respectively). Regarding the median 491 values, all results are coherent with those previously presented (Fig. 7, 8).

- This analysis supports the hypothesis that each boulder group is characterized by power-law
 and exponential-law indices that are different from the other ones.
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496 4.4 Boulder measurement uncertainties497

498 Our analysis is prone to several assumptions and sources of uncertainty. Errors and 499 uncertainties in determining the boulder shape from shadows depend, for instance, on the solar incidence angle and on the height of the boulder (Golombek et al. 2008). For a given 500 501 boulder, the greater the Sun angle above the horizon, the smaller its shadow, until the Sun is 502 directly overhead, not allowing any shadow to form. Uncertainty in the identification of boulders can also derive from ambiguity in the location of the shadow penumbra where the 503 504 direct to indirect illumination transition occurs (for details see, for instance, Golombek et al 505 2008).

506 Other papers have presented reliable results with Sun angle values of, for instance, 41° (MOC 507 images, Golombek et al 2008), 31.5° and 33.3° (HiRISE images, Golombek et al. 2008) and 508 about 36° in Golombek et al. (2012). In our case, as shown in Fig. 3a and 3b, the incidence 509 angle is 48°, allowing reliable identification of shaded and non-shaded regions, and therefore 510 of the boulders themselves.

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512 Other sources of uncertainty in our analysis are those related to the ability to differentiate 513 non-boulder features that cast shadows (such as portions of escarpments, small hills, and 514 mounds) from real boulders, and to the resolution of the images. Given that the boulders were 515 manually detected, we consider the uncertainty related to the differentiation of boulders from other features to be low, compared to the uncertainties related to the resolution of the images. 516 517 For instance, Golombek et al. (2012b), by using an automated boulder counting algorithm that fits ellipses to shadows and cylinders to the rocks, show that boulders >1.5 m diameter 518 519 are fully resolvable in HiRISE images. The authors discuss the limited capability of the 520 automated process to differentiate non-boulder features that cast shadows and the importance of visual inspection of automatically detected boulders by operators in order to exclude non-521 522 boulders from the maps. In our analysis, the map-projected HiRISE image resamples the 523 pixels to create a consistent pixel scale of 25 cm/pixel, introducing uncertainties in the estimation of the real diameter. The smaller the boulder, the bigger the relative uncertainty is; 524 525 nevertheless, in our statistical analysis we do not consider boulders with diameters <1.75 m 526 (i.e. 7 pixels), corresponding to an area of $\sim 2.7 \text{ m}^2$ (i.e. $\sim 44 \text{ pixels}$). Moreover, we point out that, by manually identifying boulders in high-resolution MOC images (Malin et al., 1998) as 527 528 pairs of light and dark pixels (bright and shaded sides) on the images, Golombek et al (2003) 529 found that "although there was some uncertainty in the identification, it was generally 530 repeatable, with different observers yielding similar results. Measured boulder diameter is probably within ±1 pixel". Such consideration, as well as the results of the sensitivity analysis, 531 532 give us confidence on the robustness and reliability of our detection and identification of boulders and on the reliability of our results. 533

534 **5.0 Discussion**

535 5.1 Comparison with SFDs in the Solar system

536 537 In order to understand what the derived Oxia Planum SFDs mean, which processes produced 538 them, and to contextualize them in the wider framework of Solar System SFD studies, we here 539 summarize the literature on boulder size-distributions obtained through remote sensing i) on 540 the Moon, ii) on asteroids, iii) on comets and iv) on Mars. We point out that there is a vast 541 literature on Terrestrial fractal fragmentation as well, e.g. Hartmann (1969), Curran et al., 542 (1977), Fujiwara et al. (1977), Wu et al., (1993), Turcotte (1997), Senthil Kumar et al., (2014), 543 but with the exception of few cases where m-sized boulders are considered, such as **Bennet** 544 (1936) and Schoutens (1979), all the presented power-law indices are derived from laboratory fragmented pebbles, hence with diameters ranging from mm to dm, but never reaching the 545 546 dimensions we identified on Oxia Planum. For this reason we cannot use them as a possible 547 **Oxia Planum comparison.**

548 On the Moon, there is important literature regarding different SFD power-law indices 549 derived from orbital imaging. The considered size-ranges are equal or comparable (1 to 50 m 550 across) to the ones used on Oxia Planum, hence they can be used as a comparison to our 551 analysis (Table 3). By using Lunar Orbiter images, Cintala and McBride (1995) have analyzed the debris fields surrounding the Surveyor I, II, VI and VII landing sites (Shoemaker and 552 553 Morris (1970) and Hartmann (1969). The resulting power-law indices range between -3.51 554 (Surveyor I landing site, evaluated in the 1-5 m range) and -6.02 (Surveyor VI landing site, 555 evaluated in the 1-4 m range). Bart and Melosh (2010) presented a wide dataset of power-law indices that were derived for several lunar craters using NASA Lunar Orbiter III, V and the 556 557 Apollo 17 dataset and evaluated in a size-range of 3 to 50 m. The power-law curves **Bart and** 558 **Melosh (2010)** used to fit the SFD have indices ranging between -3.0 to -4.5, with a single best 559 fitted case of -5.5. By using the Lunar Reconnaissance Orbiter (LRO) images, Krishna and Senthil Kumar (2016) identified a power-law index of -2.76 derived from the boulders in the 560 561 2-25 m range surrounding the Censorinus crater.

All the presented SFDs have been attributed to impact related processes since such indices, and the shapes of the fragments (when available), reflect the distributions produced by impact of a rock surface on the ground (Surveyor Scientific Evaluation and Analysis Team (1966a), Shoemaker, 1965; Melosh 1984, p. 254). The steepest power-law indices obtained on the Moon are derived through size ranges comparable to those identified in the Oxia Planum landing site and can be therefore considered as a crater-related fracturing reference for our distributions.

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loon:	Mission	Reference	Power-law index	Diameter size/Range	Notes
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Surveyor I landing site	NASA/Lunar Orbiter	Cintala and McBride (1995)	-3.51 ± 0.47	1 - 5 m	Field debris surrounding Surveyor I landing - impact related
Surveyor III landing site	NASA/Lunar Orbiter	Cintala and McBride (1995)	-5.65 ± 0.63	1 - 6.5 m	Field debris surrounding Surveyor III landing - impact related
Surveyor VI landing site	NASA/Lunar Orbiter	Cintala and McBride (1995)	-6.02 ± 1.40	1 - 4 m	Field debris surrounding Surveyor VI landing - impact related
Surveyor VII landing site	NASA/Lunar Orbiter	Cintala and McBride (1995)	-4.03 ± 0.14	10 - 65 m	Field debris surrounding Surveyor VII landing - impact related
		1		<u> </u>	
Crater III-185-H3	NASA/Lunar Orbiter III	Bart and Melosh (2010)	-4.2	3 - 10 m	Collisional Impact related to crater III-185-H3
Crater III-168-H2	NASA/Lunar Orbiter III	Bart and Melosh (2010)	-4.0	4 - 18 m	Collisional Impact related to crater III-168-H2
Crater III-186-H3	NASA/Lunar Orbiter III	Bart and Melosh (2010)	-4.0	3 - 18 m	Collisional Impact related to crater III-186-H3
Crater III-189-H2	NASA/Lunar Orbiter III	Bart and Melosh (2010)	-3.0	4 - 15 m	Collisional Impact related to crater III-189-H2
Crater V-63-H2	NASA/Lunar Orbiter V	Bart and Melosh (2010)	-3.0	10 - 70 m	Collisional Impact related to crater V-63-H2
Crater V-82-M	NASA/Lunar Orbiter V	Bart and Melosh (2010)	-3.0	50 - 320 m	Collisional Impact related to crater V-82-M
Crater V-152-H2	NASA/Lunar Orbiter V	Bart and Melosh (2010)	-5.5	5 - 18 m	Collisional Impact related to crater V-152-H2
Crater V-153-H2	NASA/Lunar Orbiter V	Bart and Melosh (2010)	-3.0	5 - 45 m	Collisional Impact related to crater V-153-H2
Crater V-167-H2	NASA/Lunar Orbiter V	Bart and Melosh (2010)	-4.0	4 - 18 m	Collisional Impact related to crater V-167-H2
Crater V-167-H3	NASA/Lunar Orbiter V	Bart and Melosh (2010)	-4.0	5 - 20 m	Collisional Impact related to crater V-167-H3
Crater V-199-M	NASA/Lunar Orbiter V	Bart and Melosh (2010)	-2.2	50 - 380 m	Collisional Impact related to crater V-199-M
Crater V-211-H3	NASA/Lunar Orbiter V	Bart and Melosh (2010)	-4.0	4 - 18 m	Collisional Impact related to crater V-211-H3
Ap17-Pan-2345a	NASA/Apollo 17	Bart and Melosh (2010)	-4.0	10 - 40 m	Collisional Impact related to crater Ap17-Pan-2345a
Ap17-Pan-2345b	NASA/Apollo 17	Bart and Melosh (2010)	-4.5	10 - 30 m	Collisional Impact related to crater Ap17-Pan-2345b
Ap17-Pan-2345e	NASA/Apollo 17	Bart and Melosh (2010)	-4.5	10 - 22 m	Collisional Impact related to crater Ap17-Pan-2345e
Ap17-Pan-2345f	NASA/Apollo 17	Bart and Melosh (2010)	-4.0	10 - 30 m	Collisional Impact related to crater Ap17-Pan-2345f
Ap17-Pan-2345g	NASA/Apollo 17	Bart and Melosh (2010)	-4.5	10 - 30 m	Collisional Impact related to crater Ap17-Pan-2345g
Ap17-Pan-2345i	NASA/Apollo 17	Bart and Melosh (2010)	-3.2	10 - 50 m	Collisional Impact related to crater Ap17-Pan-2345i
				[]	· · ·
Censorinus crater	NASA/LRO	Krishna and Senthil Kumar (2016)	-2.76	2-25 m	Collisional Oblique Impact related to Censorinus crater
	1			· · · · · · · · · · · · · · · · · · ·	

Table 3: The SFD derived for lunar boulders and the corresponding size range at which they were derived.

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591 When asteroids are taken into account, boulders or large blocks present on their surfaces are 592 interpreted to be the result of impact processes as well. Indeed, they are considered to be the largest fragments excavated during the impact as they can always be found in close proximity to craters. In 593 594 the case of the two asteroids (433) Eros and (25143) Itokawa, the high-resolution images allowed derivation of the SFD of boulders with sizes above 5 and 15 m respectively, returning a power-law 595 596 index ranging between -3.1 and -3.5 (Michikami et al., 2008; Mazrouei et al., 2014), see Table 4. 597 This range falls inside the one presented for the Moon, hence supporting an impact origin as well (Geissler et al., 1996, Thomas et al., 2001, Michikami et al., 2008, Mazrouei et al. 2014). 598 599 Nevertheless, when bigger size ranges are considered on (433) Eros, i.e. from 80 to 105 m, a steeper -6.1 power-law index has been identified, but it has been explained by **Dombard et al. (2010)** as a 600 601 result of possible depletion after an impact origin. In addition, Küppers et al., (2012) supported an impact related origin to the (21) Lutetia boulders, as a result of the north polar crater cluster 602 603 implantation.

We point out that in all asteroidal cases, the derived power-law indices are lower than the
ones we identified on Oxia Planum, with the only two cases of -6.1 on (433) Eros and -5.0 on
(21) Lutetia, where the size ranges are remarkably larger than those considered in our work.
In addition, these bodies have small-to-negligible surface gravity compared to that of Mars, so
any comparison with Martian studies should exercise caution.

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Table 4: The SFD	derived for a	asteroid boulders	and the corre	sponding size ra	ange at which they were derived.
Asteroids:	Mission	Reference	Power-law index	Diameter size/range	Notes

Asteroids:	Mission	Reference	Power-law index	Diameter size/range	Notes
(433) Eros	NASA/NEAR	Thomas et al. (2001)	-3.2	≥15 m	Collisional impact related, Shoemaker crater
(433) Eros	NASA/NEAR	Dombard et al. (2010)	-3.1	10 - 80 m	Collisional impact related, Shoemaker crater
(433) Eros	NASA/NEAR	Dombard et al. (2010)	-6.1	80 - 105 m	Depletion during implantation after impact origin
(25143) Itokawa	JAXA/Hyabusa	Michikami et al. (2008)	-3.1 ± 0.1	≥ 5 m	Impact related, Itokawa formation scenario
(25143) Itokawa	JAXA/Hyabusa	Mazrouei et al. (2014)	-3.5 ± 0.1	≥6 m	Impact related, Itokawa formation scenario
(21) Lutetia	ESA/Rosetta	Küppers et al. (2012)	-5.0	60 - 300 m	Impact related, north polar crater cluster

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A possible comparison can be made with cometary boulder SFDs that have **recently** been obtained for comets 103P Hartley 2 and 67P Churyumov-Gerasimenko. Indeed, it has been suggested that comets are affected by processes that are completely different with respect to impacts, such as sublimation, outbursts and gravitational falls, cliff regressive erosions, lifting and re-deposition (Pajola et al., 2015, 2016e,f, Mottola et al., 2015). A list of all power-law indices, the corresponding size ranges, and the related phenomena is presented in Table 5. From this table, it is possible to see

- how one of the steepest power-law **indices** observed on a Solar system body, i.e. between -5.0 to -6.5, is related to collapse/pit formation and consequent creation of depressions.
- 622 Despite similar power-law indices, the target rocks in Oxia Planum are much denser **than** the 623 cometary ones, and they are not affected by solar radiation in such **an** extreme way. This means that 624 our results are hardly comparable to cometary analyses.

626Table 5: The SFD derived for cometary boulders and families and the corresponding size range at which they
were derived.

Comets:	Mission	Reference	Power-law index	Diameter size/Range	Notes
103P Hartley 2	NASA/EPOXI	Pajola et al. (2015a)	-2.7 ± 0.2	10 - 40 m	Disintegration/fragmentation through sublimation, or lifting drag processes
67P Churyumov-Gerasimenko	ESA/Rosetta	Pajola et al. (2015b,e)	-3.6 ± 0.2	7 - 35 m	Gravitational events from regressive erosion
67P Churyumov-Gerasimenko	ESA/Rosetta	Pajola et al. (2015b,f)	-5.0 to -6.5	7 - 35 m	Collapse/pit formation and creation of depressions
67P Churyumov-Gerasimenko	ESA/Rosetta	Pajola et al. (2015b,f)	-3.5 to -4.5	7 - 35 m	Gravitational events from regressive erosion
67P Churyumov-Gerasimenko	ESA/Rosetta	Pajola et al. (2015b,f)	-1.0 to -2.0	7 - 35 m	Sublimation of not replenished cometary boulders
67P Churyumov-Gerasimenko	ESA/Philae	Mottola et al. (2015)	-2.8 ± 0.2	0.05 - 1.10 m	Mantling deposits due to particles falling back to 67P
67P Churyumov-Gerasimenko	ESA/Philae	Mottola et al. (2015)	-3.5 ± 0.3	0.39 - 2.19 m	Lag deposits on 67P

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Unlike the Moon and the asteroids, Mars hosted (and in some cases is still hosting) a wealth of processes occurring on its surface, such as aeolian and fluvial, chemical and physical erosion, tectonic events, ancient floods and freeze-thaw fracturing (Bourke et al., 2005; Viles et al., 2005). These phenomena, as well as meteor impacts, may have produced, transported and modified the original boulder size distributions. Hence, even if Mars impact-related SFDs may have been initially comparable to the ones mentioned above, they could have been completely modified throughout the ages.

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The first boulder SFDs identified on the Martian surface were derived from Viking lander 639 640 imaging. By using the NASA/Viking 1 images, Moore and Jakosky (1989) derived a power-law index of -2.66 on rocks ranging between 0.01 and 0.2 m (Table 6). Craddock et al. (1997) suggested 641 that such boulders could mainly be related to impacts, but might also be emplaced by fluvial 642 643 processes that occurred in the past on Chryse Planitia. In the case of NASA/Viking 2, Moore and 644 Jakosky (1989) derived a similar power-law index on rocks in the size range of 0.01 - 0.4 m, i.e. -2.66 (Table 6), but Thomson and Schultz (2007) suggested a different mechanism than that 645 646 thought to have occurred at Chryse Planitia to explain this size trend, i.e. an impact emplacement 647 origin or impact-derived/impact melt breccias for Utopia Planitia.

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Table 6: The SFD derived for Mars boulders and the correspond	ling size range at which they were derived.
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Mars:	Mission	Reference	Power-law index	Diameter size/Range	Notes
Viking Landing site	NASA/Viking 1	Moore and Jakosky (1989)	-2.66	0.2 m	impact related and emplacement by fluvial processes (Craddock et al., 1997 Icarus)
Viking Landing site	NASA/Viking 2	Moore and Jakosky (1989)	-2.66	0.01 - 0.4 m	impact emplaced or impact-derived/impact melt breccias (Thomson and Schultz 2007)
Pathfinder Landing Site	NASA/Pathfinder	Golombek et al. (2003)	Similar to Viking 2	0.05 - 0.4 m	Rocks between 0.5 - 0.8 m have a steeper slope (small angular ejecta versus
					semi-rounded tabular boulders carried by the flood)

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By re-analysing the Viking dataset, Golombek and Rapp (1997) introduced the exponential
model to fit the data. The model derived from fracture and fragmentation theory observed on
Earth. Their analysis was based on the evidence that power-law curves used in the previous
work provided a good fit for diameters greater than about 0.2 m, but not the smaller
diameters, which were overestimated by the power-law model. The model introduced by
Golombek and Rapp (1997) follows the exponential expression:

$$F(D) = k \exp \{-qD\},\$$

662 where k represents the fraction of surface area covered by rocks of all sizes, q is the exponent 663 of the fit, D is the diameter of the rock and F(D) is the cumulative fraction of area covered by 664 rocks with diameter bigger than D. In the case of the Viking 1 data the best fitting k value 665 equal to 0.069 was obtained and a q value equal to 4.08. In the case of the Viking 2 dataset an 666 L value of 0.176 and an s value of 2.73 were considered to be excellent fits to the data 667 (Golombek et al., (1997). In the case of the Mars Pathfinder landing site model boulder 668 distributions derived from the Viking exponential fitting curves were used in the range 0.01-669 1.5 m as well, indicating that the skewed shape of the data is similar to the boulder SFD 670 present at the two Viking landing sites (Golombek et al., 2003). We underline that the 671 presented curves are all related to sizes ranging from centimeters to ~1 m.

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673 As usually done in other analysis (e.g. Golombek et al 2008, 2012, Hebrard et al 2012), we 674 compare our results (derived from orbital images) with in-situ analysis (Viking and 675 Pathfinder data). In particular, Fig. 10 shown the cumulative fractional area occupied by 676 boulders \geq D together with the exponential-law family of curves of boulder coverage derived 677 by Golombek et al 2003.

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Fig. 10. Cumulative fractional area covered by boulders greater than diameter D versus
boulder diameters on the entire Oxia Planum study area and on the Av and Nc units,
respectively. The lines are the model distributions as from Golombek et al. (2003) for 5% to
10%, 20%, 30% and 40% boulder coverage.

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As expected, Fig 10 shows that the boulder spatial density for the Av unit is much higher than that for the Nc unit (also visible in the HiRISE image, see for instance Figs. 7 and 8). In particular, the Av unit shows a cumulative fractional area F(D) one-order greater than the Nc unit. By comparing our results with the three curves presented in Fig. 17 of Golombek et al. (2008) and indicated as "few rocks", "moderately rocky" and "very rocky", we conclude that our Nc curve is comparable to the "moderately rocky" one. On the contrary, both the global Oxia Planum curves, as well as the Av curve, are all above the moderately rocky range, with the Av unit showing a trend that is central between the "moderately" and the "very rocky" curves.

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696 As a consequence of the limited resolution of the images, the data flatten considerably at 697 boulder diameters <1.75 m. Fig. 10 also shows differences between the data and the model 698 curves. The same behavior was observed in Heet et al. (2009), that counted rocks on HiRISE 699 images from the Phoenix landing site. Such differences can be due to different processes 700 occurring at the Viking and Mars Pathfinder landing sites (data from which were used to derive the curve represented in Fig. 10) and those processes occurring at Oxia Planum. 701 702 Another possible explanation, as suggested by Heet et al. (2009), is that a simple exponential-703 law based on fracture and fragmentation theory used to derive the model curves does not fully 704 explain the boulder populations at the Phoenix landing site. Indeed, this can be true for the proposed Oxia landing site as well, where resurfacing and/or degradation events that 705 706 occurred on this region, as suggested by Quantin et al., 2016, may have completely changed 707 the original SFDs, hence making the derived curves deviate from the modeled ones.

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710 5.2 Boulder density comparison with other NASA Mars landing sites

To put our boulder densities into context, we collected the available datasets derived from previous NASA Mars landed missions. We are aware that our data were obtained through orbital imaging, but we consider only the boulder densities obtained by lander missions for clast sizes comparable to our case study, i.e. boulders \geq 1.75 m.

716 Golombek and Rapp (1997) analyzed both the Chryse and the Utopia Planitia landing sites of the Viking 1 and 2 missions. By using their exponential SFD, spatial densities of 3.9×10^{-9} /m² and 717 718 3.4×10⁻⁶/m² for boulders \geq 1.75 m are derivable for the Viking 1 and 2 landing areas, respectively. Contrarily, Golombek et al. (2008) presented a much higher spatial density (close to $1.0 \times 10^{-4} \text{ m}^{-2}$) 719 for boulders \geq 1.75 m at the Mars Pathfinder landing site. All three landing sites fall within the 720 721 rockiest 15% of the planet (Golombek 2003a,b), but the Mars Pathfinder landing area is located on 722 a much rougher and rockier surface than either of the Viking landers, i.e. at the outlet of the Ares 723 Vallis on Chryse Planitia.

Despite the maximum sizes of 1.5 m that are presented, similar boulder spatial densities to those at the Viking landing sites have been obtained by the Spirit rover during its traverse across Gusev crater (Golombek 2006). For example, the densities performed on the Columbia Memorial Station on Gusev have been shown to be generally lower than those of Viking 1, while they rapidly increase towards the rim of the Bonneville crater, reaching values similar to the Viking 2 landing area.

In the case of the Phoenix lander on Vastitatis Borealis, i.e. the largest lowland region on the northern plains of Mars, Golombek et al. (2012a) derived a density of boulders \geq 1.75 m across that is lower than $1.0 \times 10^{-6}/m^2$, i.e. considerably smaller than the density at the Mars Pathfinder landing site.

734 Measurements performed for Gale crater using HiRISE images indicate a spatial density of 735 5.0×10^{-5} /m² for boulders that are ≥ 1.75 m (Golombek et al., 2012b).

736 It is evident that the geomorphological settings of the summarized sites are different. 737 Nevertheless, if we compare the Oxia boulder densities with those presented above, it is 738 unambiguous that our study area presents much higher values (i.e. $6.75 \times 10^{-4}/m^2$). Peak values are obtained for the Av unit (i.e. $1.79 \times 10^{-3}/\text{m}^2$), whilst the Nc one has a density of $2.55 \times 10^{-4}/\text{m}^2$: comparable, but still slightly higher, than the Mars Pathfinder landing site.

It is true that we do not know how the Oxia boulder size distribution **appears** when sizes smaller than 1.75 m are considered, nor their densities per m². Nevertheless, this comparison suggests that a careful evaluation of the risks related to this landing spot, and in particular to the Av unit, has to be taken into consideration **given its moderately to very rocky nature**.

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746 **5.3 Boulder production/preservation**

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A higher value of the power-law index means that i) production rates are different and/or ii)
processes decreasing the population of the larger boulders and replenishing the smaller size
frequencies should have been active.

Martian weathering processes currently **involve** wetting/drying and freeze/thaw cycles, along with thermal shocks due to topographic shading, and they likely act in a similar way **for** any given lithology (Leask and Wilson, 2003). For this reason, the amount of time **over** which alteration processes have occurred becomes the prominent factor. In the Oxia case, the SFD power- and exponential-indices of the Nc unit are steeper than the Av one (Fig. 8), despite its shorter exposure time. For this reason, a different production rate of boulders should be considered for the two separate units.

The two geological units not only show different SFD power-law indices, **but are also characterized by varying boulder spatial density. The** Av unit has a density 7.0 times **larger** than **that of** the Nc (1788 /km² versus 255 /km² boulders \ge 1.75 m, respectively). This ratio could be even **larger** if different sectors of Oxia Planum are considered, since **the study area features** ejecta of a 230 m wide crater located near the center of the Nc unit (Fig. 8, black arrows), increasing the local density of boulders (Fig. 7b). The main driver for this difference may **therefore be** the different lithologies where impacts occurred.

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766 When meteor impacts occur, shock waves are generated. These waves are produced when the 767 involved energy is large enough to overcome the threshold between elastic and inelastic behavior of rocks (Jaeger et al., 2007). As mentioned before, the Av unit is composed of basaltic lava flows, 768 769 whereas the Nc one is a clay-rich formation, most likely sedimentary in origin. According to Ahrens 770 and Johnson (1995), shock waves propagate at higher velocities in basalts than in sedimentary 771 rocks. More precisely, velocities are two-to-four times higher in the basaltic case, with greater 772 energy dissipation in the sedimentary lithologies. Moreover, basaltic lava flows and **clay-rich** rocks 773 have different mechanical properties (Chevrier and Mathé, 2007; Hausrath et al., 2008; Yesavage et al., 2015), possibly affecting boulder production/preservation. In particular, igneous rocks have a 774 775 much higher dynamic strength (three-to-ten times more) than sedimentary ones (Ai and Ahrens, 2004). This property, as well as the volatile content of target rocks, will also influence melt 776 generation at impact, with less cohesive rocks producing increased runout and fluidization of 777 ejecta, instead of production of ballistic projectiles (Osinski et al., 2011). Smaller shock wave 778 779 velocities and dynamic strengths, as for the sedimentary rocks, suggest the production of a larger 780 number of cracks in sedimentary rocks that would then produce smaller and more abundant 781 boulders. On the contrary, the igneous ones should produce fewer, but larger, blocks. Our SFD 782 results are in good agreement with this theoretical framework, whilst boulder densities are not. However, the much higher exposure age of the Av unit may account for this latter aspect, since it 783 784 implies a higher number of impacts, producing a larger amount of boulders in all sizes.

Besides the nature of target rocks, detailed studies on terrestrial craters suggest that other factors should be evaluated too. Lonar Crater is a 1.9 km wide impact crater located in Buldhana district, Maharashtra, India. It formed during the Pleistocene Epoch on the Deccan basalt province, one of the largest igneous **provinces** on Earth, **composed** mainly **of** tholeiitic basalts. In the interior walls

789 of the Lonar Crater up to six individual lava flows are exposed (Maloof et al., 2010), thus making it 790 a good analog for craters located on our Av unit. Meteor Crater (also known as Barringer Meteorite 791 Crater) is a 1.2 km wide impact crater located in Arizona, USA. This is the result of an iron asteroid 792 impact on layered sedimentary rocks during the Pleistocene Epoch (Kring, 2007), possibly 793 representing a good analog for our Nc unit. The analysis of fracture systems of these two craters 794 highlights the prominent role of pre-impact structures in determining the stress propagation, 795 crater rim uplift, final crater shape, fragmentation and preferential erosion (Kumar and Kring, 796 2008). Pre-impact conditions such as weathering, layer thickness, and preexisting cracks/fractures 797 are believed to affect also the sizes of boulders constituting the crater's ejecta (Kumar et al., 2014). 798 For the Lonar Crater case, the ejecta are mainly fine-grained (i.e. gravel/sand), nonetheless 799 boulder clusters have been found in various sectors, with clasts ranging from <1 m to 7.2 m in size. 800 These boulders are partially buried by the ejecta; hence they should be considered as a minimum size term (Kumar et al., 2014). As for the Meteor Crater ejecta, less detailed information is 801 802 available; however, it is mentioned that the **boulders** in the ejecta range from 0.5 to 30 m in size 803 (Shoemaker, 1987; Ramsey, 2002).

Despite large tectonic **structures are likely** to have affected in a similar way all involved Oxia geological units, this is not the case of intrinsic conditions related to a specific lithology, such as planar bedding of strata or the formation of cooling joints. The calculated SFD **suggests** that no major weakening structures perturbed the lithologies, or that they have been equally affected.

809 The presented hypotheses need a fundamental validation that can only be accomplished by the 810 future ExoMars rover, which will land on Oxia Planum in 2020. The foreseen panoramic images that will be provided by the Wide Angle Camera of the PanCam instrument (Coates et al., 2015), 811 812 mounted on the mast of the ExoMars rover, will provide a unique opportunity to test our 813 interpretations. Indeed, while travelling towards its multiple targets, the PanCam will provide several views of different terrains and textures, and hence, will create the opportunity to perform 814 815 the SFD computation from boulder sizes ranging from meters to centimeters. This will not only test 816 our analysis, but it will also extend our SFD to the smaller sizes. In addition to the SFD 817 identification, such observations will provide evidence of what kind of processes occurred and/or are possibly still active on the surrounding boulders. 818 819

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821 5.4 ExoMars 2020 navigability implications

822 The ExoMars rover has a mass of 220 kg (56 kg being the payload mass) and a size of 1.2 m x 1.1 823 m x 2.0 m (http://exploration.esa.int/mars/45084-exomars-rover/), with a ground clearance of 30 cm 824 (see ExoMars 2018 Landing Site Selection User's Manual, Version 1.0, 17 December 2013, hereafter: EXM-SCI-LSS-ESA/IKI-003), i.e. similar to the 29 cm of the Mars Exploration rovers 825 (MER, Leger et al., 2005) and half that of the Mars Science Laboratory, MSL 826 (http://mars.nasa.gov/msl/mission/timeline/firstdrive/). This means that every object bigger than 20 827 cm has to be considered hazardous and must be avoided as indicated in the ExoMars Landing 828 829 site selection User Manual: http://exploration.esa.int/mars/53458-exomars-2018-landing-site-830 selection-users-manual/ Reference: EXM-SCI-LSS-ESA/IKI-003. Moreover, a lateral clearance 831 of about 2-3 m from obstacles is desirable, given sufficient operating area. The ExoMars 832 locomotive system is characterised by 6 wheels on a 3-bogie system and each wheel is equipped with 3 actuators: drive, steer and deployment (or wheel walking); this means that contrarily to the 833 MER and MSL, all 6 wheels of the rover can drive and steer simultaneously, providing major 834 835 manoeuvrability/controllability (Silva et al., 2013). This will mean that there is the possibility to 836 steer and drive closer to obstacles than previous missions have managed, although only in 837 unavoidable cases.

838 The ExoMars rover has been planned to achieve two of the most challenging requirements ever tried on the surface of another planet, i.e. the ability to drive an average distance of 70 m per sol (a 839 840 sol is a Martian day and lasts ~24h37m) and to be able to continue performing its mission without 841 contacting Earth for 2 sols (EXM-SCI-LSS-ESA/IKI-003). It has to be considered that the Martian surface is characterized by several challenges for a rover to drive over, ranging from visible 842 843 obstacles such as rocks, steep slopes (up or down), and craters, to dangerous situations such as 844 slippage. For all these reasons, and in order to **minimize hazards** whilst driving, it is equipped 845 with an autonomous navigation system, supported by the combination of the following devices 846 (Silva et al. 2013):

- a sun sensor, that permits an absolute localization on Mars;
- an accelerometer, used to obtain an absolute reference of the rover roll and pitch (or/and tilt angle) by measuring the Martian gravity vector;
- a gyroscope, used to propagate the rover attitude;
- panchromatic stereo cameras (at about 2 m above the ground mounted on a pan-tilt assembly) and navigation cameras, in order to provide visual localization of obstacles.

The rover can therefore **be** controlled from Earth with various levels of commanding, executing low-level manoeuvre commands, such as Ackerman curves, point turns, or crabbing, or performing on-board path planning. Nevertheless, greater autonomy will be given to the rover after multiple quantitative evaluations of the terrain type and its characterization, with particular focus on the boulder size-distribution analysis, which is one of the main hazards during navigability.

- 858 Our boulder spatial statistics **represent** a reasonable basis to quantify what is the minimum surface 859 percentage that will be unreachable **by** the rover, expressed as a function of the distance from the 860 obstacles. We have considered two representative test case areas, 450m x 400m wide (total area of 861 $1.8 \times 10^5 \text{ m}^2$), in the Nc (center: 24°31'30''W-18°13'56''N) and Av (center: 24°31'28''W-862 18°15'11''N) units. We have computed seven different distance ranges centered on each boulder 863 $\geq 1.75 \text{ m}$ **across**, from 1 to 20 m, to understand how, and at **what** distances, the rover can travel 864 between two or multiple obstacles.
- As it is possible to see from Fig. 11, when the Nc unit is considered, navigable paths can be 865 identified even with a safety distance of 20 m, while there are almost no inaccessible areas at values 866 867 <10 m. Contrarily, in the case of the Av unit, proper navigable paths have to be carefully studied and identified even at the safety distance of 2-3 m, this becoming particularly rougher if distances > 868 869 4 m from the obstacles are considered. Traveling on the Nc unit will be much easier with respect 870 to the Av one, indeed the cumulative fractional area covered by boulders \geq diameter D presented in Fig. 10 shows that the Av unit is much rockier than the Nc one. Moreover, the Nc 871 unit has a density of boulders per m^2 which is 7.0 times smaller when compared to the Av 872 873 unit. leading to a larger autonomy to the rover navigation system. Hence, the foreseen scientific
- return of the mission can be greatly enhanced if the Nc unit will be the final landing area of the rover.
- 876





Nc unaccessible area: 0.52%

Nc unaccessible area: 9.99%







Nc unaccessible area: 4.17%

Nc unaccessible area: 27.58% Nc unaccessible area: 56.77%

 Av unaccessible area: 2.52%
 Av unaccessible area: 9.53%
 Av unaccessible area: 19.21%

 Image: Av unaccessible area: 2.52%
 Image: Av unaccessible area: 2.52%
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Fig. 11. Upper-left corner: map showing the locations of the two landing test areas in the Nc and in the Av unit. Other images show the buffer distances from the boulders (red areas). The percentages of the areas unreachable by the ExoMars 2020 rover are shown too.

Av unaccessible area: 29.81% Av unaccessible area: 40.15% Av unaccessible area: 74.73% Av unaccessible area: 92.93%

6.0 Summary and Conclusions-----

Nc unaccessible area: 6.89%

We studied a circular area **of** 12.57 km² that is located at the center of the ExoMars Oxia Planum **prime** landing ellipse. Here, both the Noachian clay-rich formation (Nc), as well as the Amazonian volcanic deposit (Av), i.e. the two main units that constitute the entire region, are present.

Using a HiRISE image (0.25 m/pixel), boulders and fine-grained deposits have been mapped.
Whilst the former proved to have been properly sampled for sizes bigger than 1.75 m, allowing for
additional analysis, the latter appear not to bias the boulder sampling. We derived a global density

of boulders of 6.75×10^{-4} /m² and size-frequency indices of -4.9 + 0.1/-0.2 (power-law fit) and -1.29894 +0.04/-0.06 (exponential-law fit) obtained in the range 1.75-6.75 m. When compared to other Mars 895 896 landing sites observed from orbiters and landers, both the SFD fitting curves and the density of boulders per m² indicate that this area is moderately to very rocky (Golombek et al., 2008). Indeed, 897 our study area presents higher values (i.e. $6.75 \times 10^{-4}/m^2$) than all previous Mars landing sites. Peak 898 899 values are obtained for the Av unit (i.e. 1.79×10^{-3} /m²), whilst the Nc one has a density of 2.55×10^{-5} $^{4}/m^{2}$, comparable, but still slightly higher, than the Mars Pathfinder landing site. 900

When the Av and the Nc units are considered separately, we identified different SFD 901 power- and exponential-law indices showing a clear higher absolute amount of boulders of all 902 903 sizes in the Av unit, when compared to the Nc one. This is corroborated by the extremely different density of boulders, that is 7.0 times larger for the Av unit with respect to the Nc one 904 $(17.88 \times 10^{-4} \text{ versus } 2.55 \times 10^{-4} \text{ boulders} \ge 1.75 \text{ m per m}^2)$. The Av unit deposited above the Nc unit, 905 covering it, therefore a heavier meteoritic occurrence coupled with weathering effects can be 906 907 invoked to explain this difference. However, these two units are remarkably different in origin, the 908 younger being volcanic (Av) and the older sedimentary (Nc). Specific differences in rock 909 mechanics, such as shock wave velocities and dynamic strengths, suggest the production of a larger 910 number of cracks in sedimentary rocks, which would then result in smaller and more abundant 911 boulders. Our SFD results are in good agreement with this theoretical framework, whilst boulder 912 densities are not. However, the much higher exposure age of the Av unit may justify that, **implying** 913 a higher number of impacts, hence a general larger amount of boulders at all sizes.

914 The discussed hypotheses can only be validated by means of in situ ExoMars observations, 915 which can provide information of different terrains and textures. Indeed, with the ExoMars dataset, 916 the SFD computation of boulder sizes ranging from meters to tens of centimeters will be performed 917 and linked with more precision and detail to the processes that have occurred/are still occurring on 918 the Oxia Planum surface.

919 In addition to the scientific implications that have been derived from the presented results, this 920 study provides the quantitative measurements of the **boulder** abundances ≥ 1.75 m across for the 921 two geological units identifiable on the future ExoMars 2020 landing site. For this reason, it can be used as a possible reference for safety engineering constraints, both during the landing phase and 922 the roving traverse to specific regions of interest. In order to quantify what is the minimum surface 923 924 percentage that will be unreachable by the rover, we have considered two representative test case 925 areas centered in the Nc unit, and in the Av unit, respectively. We have then computed seven 926 different lateral clearance ranges centered on each boulder ≥ 1.75 m, from 1 to 20 m, to understand 927 how and at what distances the rover can travel between two or multiple obstacles. The performed 928 analysis suggests that landing on the Nc unit, rather than on the Av unit, will result in faster 929 and farther navigability of the rover to a specific science target, greatly enhancing the 930 scientific return of the mission.

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