



# Analyses of robotic traverses and sample sites in the Schrödinger basin for the HERACLES human-assisted sample return mission concept

DOI:

[10.1016/j.asr.2016.05.041](https://doi.org/10.1016/j.asr.2016.05.041)

## Document Version

Accepted author manuscript

[Link to publication record in Manchester Research Explorer](#)

## Citation for published version (APA):

Steenstra, E. S., Martin, D. J.P., McDonald, F. E., Paisarnsombat, S., Venturino, C., O'Hara, S., Calzada-Diaz, A., Bottoms, S., Leader, M. K., & Klaus, K. K. (2016). Analyses of robotic traverses and sample sites in the Schrödinger basin for the HERACLES human-assisted sample return mission concept. *Advances in Space Research*. <https://doi.org/10.1016/j.asr.2016.05.041>

## Published in:

Advances in Space Research

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1 **Analyses of Robotic Traverses and Sample Sites in the**  
2 **Schrödinger basin for the HERACLES Human-Assisted**  
3 **Sample Return Mission Concept**

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19

20 **Abstract**

21

22 Near-future exploration of the Moon will likely be conducted with human-operated robotic assets.  
23 Previous studies have identified the Schrödinger basin, situated on the far side of the Moon, as a prime  
24 target for lunar science and exploration where a significant number of the scientific concepts reviewed  
25 by the National Research Council (NRC, 2007) can be addressed. In this study, two robotic mission  
26 traverses within Schrödinger basin are proposed based on a 3 year mission plan in support of the  
27 HERACLES human-assisted sample return mission concept. A comprehensive set of modern remote  
28 sensing data (LROC imagery, LOLA topography, M<sup>3</sup> and Clementine spectral data) has been  
29 integrated to provide high-resolution coverage of the traverses and to facilitate identification of

30 specific sample localities. We also present a preliminary Concept of Operations (ConOps) study based on  
31 a set of notional rover capabilities and instrumental payload. An extended robotic mission to  
32 Schrödinger basin will allow for significant sample return opportunities from multiple distinct geologic  
33 terrains and will address multiple high-priority NRC (2007) scientific objectives. Both traverses will offer  
34 the first opportunity to (i) sample pyroclastic material from the lunar farside, (ii) sample Schrödinger  
35 impact melt and test the lunar cataclysm hypothesis, (iii) sample deep crustal lithologies in an uplifted  
36 peak ring and test the lunar magma ocean hypothesis and (iv) explore the top of an impact melt sheet,  
37 enhancing our ability to interpret Apollo samples. The shorter traverse will provide the first opportunity  
38 to sample farside mare deposits, whereas the longer traverse has significant potential to collect SPA  
39 impact melt, which can be used to constrain the basin-forming epoch.

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41 **Keywords:** Schrödinger, Moon, Exploration, Lunar, Sample Return Mission

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### 43 **1. Introduction**

44 The international community agrees (e.g., NRC, 2007; Crawford et al., 2012) that exploration of the  
45 Moon can address fundamentally important scientific questions, while providing a credible path for  
46 human exploration into the Solar System. The International Space Exploration Coordination Group  
47 (ISECG), an interagency organization developing an integrated Global Exploration Roadmap (GER), is  
48 currently exploring a human-assisted robotic sample return mission concept (HERACLES; Human-  
49 Enhanced Robotic Architecture and Capability for Lunar Exploration and Science). This mission concept  
50 involves a series of landings that would expand access to the lunar surface. The first landing would  
51 deploy the rover. Two additional landings of a reusable ascent vehicle at other sites along the traverse  
52 would deploy a suite of experimental packages. The rover collects samples and performs in-situ analyses  
53 during each section of the traverse for a number of months, and rendezvous with the ascent vehicle to  
54 transfer the collected samples. A crew in the Orion capsule or an exploration Deep Space Habitat (eDSH)  
55 could tele-operate the rover while orbiting at the Earth-Moon L2 Lagrange point above the farside of the  
56 Moon (Burns et al., 2013; Pratt et al., 2014). The samples for each section would then be transferred  
57 from the ascent vehicle to the eDSH, which would transfer the samples to the Orion crew vehicle for  
58 return to Earth.

59 One of the most comprehensive studies of lunar science objectives conducted by the US National  
60 Research Council produced a report that outlined eight scientific concepts and thirty-five prioritized  
61 investigations (NRC, 2007). A large number of studies were then conducted to determine the locations

62 on the lunar surface where those investigations could be addressed (Kring and Durda, 2012). This work  
63 showed that the Schrödinger basin, situated within the South Pole-Aitken (SPA) basin, is the best  
64 location on the Moon for addressing the highest priority and largest number of objectives.

65 For example, a robotic sample return mission to Schrödinger basin would test the cataclysm  
66 hypothesis (NRC Goal 1), would provide insights into the the petrologic structure of the lunar interior  
67 (NRC Goals 2 and 3), would assess the thermal and compositional evolution of the Moon (NRC Goals 3  
68 and 5), would provide insights into basin forming processes (NRC Goal 6) and would investigate regolith  
69 processes and surface weathering (NRC Goal 7). A recent study of Kumar et al. (2015) suggests that the  
70 Schrödinger basin is also an interesting locality for studying local seismic events and could be tied into a  
71 tetrahedral seismic array for global lunar coverage (Tian et al., 2013). In addition, several targets within  
72 the peak ring structure are likely to receive no or little illumination year-round and are therefore  
73 believed to be targets suitable for in-situ resource utilization (ISRU) (Kring et al., 2014; NRC Goal 4). The  
74 pyroclastic vent is believed to be a prominent source of volatiles and, therefore, also has a significant  
75 ISRU potential (Kring, 2014). Previous studies have referenced these benefits to justify a range of sites  
76 and traverses that are located within the Schrödinger basin. However, these mission designs involved  
77 either human exploration on the lunar surface (Bunte et al., 2011; O’Sullivan et al., 2011) or a robotic  
78 exploration mission that does not exceed more than one lunar day (Potts et al., 2015).

79 In this study, two possible traverses for long-term (~3 year) robotic exploration in the Schrödinger  
80 basin are investigated by integrating a wide range of remote sensing datasets that include topography,  
81 compositional spectra, and high-resolution imagery (Martin et al., 2016; McDonald et al., 2016). The  
82 proposed traverses are based on previously identified key targets within Schrödinger basin (O’Sullivan et  
83 al., 2011; Potts et al., 2015; Hurwitz and Kring, 2015) and are designed to address the key science and  
84 exploration objectives that are prevalent throughout the international lunar science community (NRC,  
85 2007; Crawford et al., 2012).

86

## 87 **2. The Schrödinger basin**

88 The Schrödinger impact basin (Fig. 1, 2) is located on the lunar farside (-75°, 132.5°) and is the second-  
89 youngest basin formed during the basin-forming epoch. It is situated within the South Pole-Aitken (SPA)  
90 basin, the oldest and largest impact basin on the Moon. Schrödinger measures ~320 km in diameter and  
91 its basin floor has a minimum elevation of ~4.5 km below the crater rim. Despite subsequent  
92 modification by both volcanism and secondary cratering from nearby large impacts, Schrödinger is  
93 remarkably well preserved. It features a distinctive inner peak ring measuring ~150 km in

94 diameter, extending up to ~2.5 km above the basin floor, and possessing a discontinuous  
95 southern region due, probably, to overlapping with the Amundsen-Ganswindt basin (Shoemaker et al.,  
96 1994). The peak ring preserves pre-Schrödinger materials uplifted from a depth of ~20-30 km, implying  
97 the presence of mid- to deep-crustal lithologies (Kring et al., 2013). The modification of Schrödinger  
98 basin is likely to have exposed SPA-derived material within its southern wall which would be of great  
99 significance as sampling this material would address the two top ranking NRC (2007) science objectives  
100 (Hurwitz and Kring, 2015).

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Fig. 1, Fig. 2

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### 104 **3. Methods**

105 Traverse routes within the Schrödinger basin were constructed in ArcGIS© 10.1 using Lunar  
106 Reconnaissance Orbiter Camera (LROC) NAC (Narrow Angle Camera; 0.5 m/pix resolution) and WAC  
107 (Wide Angle Camera; 100 m/pix) images, integrated with a Digital Elevation Map (DEM from Lunar  
108 Orbiter Laser Altimeter). Spectral reflectance data, collected by M<sup>3</sup> and documented in the geologic map  
109 of Kramer et al. (2013), was also used to supplement these datasets to select sample sites along  
110 traverses. The WAC images were combined with Lunar Orbiter Laser Altimeter (LOLA) data to create a  
111 DEM with a spatial resolution of 100 m/pix. A set of 3D images were created by combining NAC imagery  
112 and the DEM in ArcScene©. Spectral data from the Clementine mission were used to interpret the FeO  
113 variability across the basin (Lucey et al., 2000; Kramer et al., 2013; Hurwitz and Kring, 2015).

114

### 115 **4. Rover capabilities and operations**

#### 116 *4.1 Rover capabilities and notional instrument payload*

117 The interpretation of returned samples benefits significantly from knowledge of the geological  
118 context of the sampled area. A first order criterion for instrument selection is, therefore, their  
119 demonstrated capability to provide regional and lateral geological context of the sample site. A  
120 notional payload that might be used to perform in-situ analyses along the proposed traverse include a  
121 Ground Penetrating Radar (GPR) (ExoMars WISDOM, Shearer et al., 2010), a HD imager (Mars Science  
122 Laboratory MastCam, Shearer et al., 2010), a Gamma Ray Spectrometer or GRS (JH APL, Wieczorek et  
123 al., 2015) and a Microscope Imager (MI) (Mars Exploration Rover, Arvidson and May, 2010). Other  
124 instruments may include an arm-mounted Alpha Particle X-Ray Spectrometer or APXS (Mars  
125 Exploration Rover, Arvidson and May, 2010) and a Neutron Spectrometer or NS (Lunar Prospector /

126 Hydra, Shearer et al., 2010).

127 A continuously operating GPR would provide a measure of the lateral and vertical distribution  
128 of subsurface lithologies along the traverses and a HD camera would be used to image different areas  
129 along the traverse to provide regional geological context. A MI can be used to investigate the physical  
130 and chemical properties either of the target material at the sub-millimeter scales, or adjacent  
131 material to provide additional geological context. Subsurface (<10 cm) elemental abundances for a  
132 wide range of elements can be obtained using a GRS in conjunction with an arm-mounted APXS. The  
133 APXS is particularly important as it can provide rapid compositional analysis (~30-60 minutes) of the  
134 target material with a reasonable degree of accuracy (Rieder et al., 2003). Operation of a NS would  
135 assess volatile composition and distribution and, therefore, provide a measure of ISRU potential  
136 within the Schrödinger basin. To sample regolith or other poorly consolidated material, a percussive  
137 scoop or shovel tool would be required (Craft et al., 2009; Zacny et al., 2009). Collection of uniformly  
138 sized lithic fragments would require a rake tool, which may have to be developed.

139 Sampling of boulders and outcrops along the traverse also requires the robotic asset to remove  
140 these samples without completely destroying textural data. Techniques that could be implemented  
141 include coring devices (Johnson et al., 2009; Myrick et al., 2012; Paulsen et al., 2012; Zacny et al.,  
142 2012, 2013) or rock chipping devices (Barnouin-Jha et al., 2004). Prior to identification and analysis  
143 procedures, a Rock Abrasion Tool (RAT) could be used to expose the interior of lunar rock samples  
144 (Myrick et al., 2004).

145 Technical aspects of the assumed notional instrument payload, including weight and average  
146 power consumption, are summarized in Table 1. The proposed traverses in this study could be  
147 explored with any instrument payload and the notional payload included here is simply used to  
148 demonstrate the science potential of the traverses and to create a rational concept of operations  
149 from which to determine analytical timelines and data bandwidths. The rover speed is assumed to be  
150 0.36 km/hr based on the expected speed of the Resource Prospector rover (Loftin et al., 2013), a  
151 conservative estimate given the speed of 0.8-2 km/hr of the Soviet Lunokhod rover (Seeni et al.,  
152 2010). We consider a maximum traversable slope of 16°, because wheel enabled systems show  
153 considerable difficulties at higher slopes due to a sudden drop in slip ratio (Seeni et al., 2010; Potts et  
154 al., 2015).

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Table 1

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#### 4.2 Concept of Operations (ConOps)

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Table 2

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#### 4.3 Soil mechanics and rover trafficability

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The operations that the rover will perform at stations as well as start-up and packing down processes required for traversing along the lunar surface are defined as the ConOps. The HERACLES human-assisted sample return mission concept is based on a 3 year mission duration and the rover must therefore be able to survive a large number of lunar nights (~14 Earth days) during which it will hibernate. This strategy is similar to the Lunokhod 1 rover that survived for 7 to 11 lunar nights and Lunokhod 2 that survived ~5 lunar nights (Petrov, 1972; NASA Space Science Data Center, 1970, 1973). The time estimated to deploy the rover is ~20 hours (Potts et al., 2015). Before and after each hibernation period, ~24 hours is allocated for powering down and up of the rover (Potts et al., 2015). During lunar days (~14 Earth days), we assume constant rover operation which would require that teams in Orion and on Earth dually conduct rover operations. Each of the three sample transfer procedures from the rover to the ascent vehicle are estimated to take ~10 hours (Potts et al., 2015).

Along the traverse, sampling and in-situ analysis stations were identified. At each sampling station, the rover will first stop to collect a GigaPan panorama using the surface imaging camera (~8 hrs). The rover will then select a target and will move to its location, where it will position itself (~0.5 hrs). Once in place, the rover is expected to conduct a number of analyses, including APXS (~3.5 hrs/analysis), GRS (~1.5 hrs/analysis) and MI (~1.5 hrs/analysis). The GPR is expected to operate constantly while traversing, but NS analyses would only be used at specific targets (~6.5 hrs/analysis). Images taken before and after sampling will provide context for the returned samples (~1 hr). An additional ~4 hours is required for sample collection (~3 hrs) and storage (~1 hr). Assuming one APXS, MI and GRS analysis, ~19.5 hours would be spent at each sampling station (Table 2). For in-situ analysis stations, the average time spent at each station is estimated to ~15.5 hours. This does not take into account any additional time that may be required to repeat analyses, load commands, or to address unforeseeable issues (e.g., obstacle avoidance or stuck wheels). There is, however, plenty of margin in the ConOps schedule to mitigate these types of issues as described below.

Lunar soil properties may affect the maneuverability and power usage of a robotic rover and is an important constraint on possible traverse designs. Photographic observations of footprints and Lunar Roving Vehicle (LRV tracks) from the Apollo era allow for the calculation of surficial porosity, cohesion,

190 and friction angles of lunar regolith (Mitchell et al., 1972). These results suggest that the rims of  
191 primary and secondary craters covered with significant amounts of ejecta should be circumvented  
192 due to their low trafficability. For example, the Lunokhod 2 rover experienced significant wheel  
193 sinkage (~20 cm) when it traversed the soft soils within the rim of a Mare Serenitatis crater (Carrier et  
194 al., 1991). The wall slump material within Schrödinger basin may be analogous to the soft soils  
195 encountered on Apollo 15, during which the LRV rover wheels sank ~13 cm into the lunar regolith  
196 (Carrier et al., 1991). However, the weight of the rover is likely to be significantly lower than the LRV  
197 and its much lower speed would reduce wheel spin, which would reduce the risk of significant wheel  
198 sinkage. A particular area of interest is the pyroclastic unit within Schrödinger, because the physical  
199 properties of lunar pyroclastic soils are poorly constrained. Apollo 17 regolith core samples from the  
200 Shorty crater rim suggested that the orange glass deposit was unusually compact, exhibiting high  
201 cohesion (Mitchell et al., 1973). The bearing capacity of a lunar soil is defined as its capability to  
202 support applied loads and is therefore a proxy for possible trafficability of a lunar rover. Using the  
203 surficial properties obtained for the upper part of the latter drill core combined with observed  
204 boulder tracks within the pyroclastic deposits close and within the vent (the Appendix), the bearing  
205 capacity of the pyroclastic material can be calculated using Terzaghi's bearing capacity equation for  
206 circular footings (Terzaghi, 1948) (Eq. 1):

$$207$$
$$208 \quad Q = 1.3 N_c C + \rho g N_q D_f + 0.6 \rho g N_\gamma R_f \quad (1)$$
$$209$$

210 where  $N_c$ ,  $N_q$ , and  $N_\gamma$  are dimensionless numbers for soil shear conditions based on the internal friction  
211 angle. The boulder and associated track dimensions were used for the depth of footing ( $D_f$ ) and radius  
212 of footing ( $R_f$ ) values (Fig. 2). Cohesion ( $C$ ) value is taken to be  $10^3$  dynes/cm<sup>2</sup> (Moore, 1970; Hovland  
213 and Mitchell, 1969; Mitchell et al., 1973), gravity ( $g$ ) as  $163$  cm/s<sup>2</sup> and the boulders are assumed to be  
214 spherical. Assuming an internal friction angle of  $30^\circ$  and estimated pyroclastic soil density of  $2.0$  g/cm<sup>3</sup>  
215 (Moore, 1970; Hovland and Mitchell, 1969; Mitchell et al., 1973), we calculate a bearing capacity ( $Q$ ) of  
216  $3.46 \times 10^6$  dynes/cm<sup>2</sup>, comparable to the  $9.28 \times 10^5$  dynes/cm<sup>2</sup> calculated by Moore (1970) for general  
217 lunar surface capacities (the Appendix). The friction angle of lunar pyroclastic deposits is not known.  
218 However, an increase of the friction angle to  $35^\circ$ , the suggested value for the upper 15 cm of regolith  
219 (Houston et al., 1972; Hovland and Mitchell, 1969; Mitchell et al., 1972, 1973), results in an increase of  
220 the bearing capacity to  $6.41 \times 10^6$  dynes/cm<sup>2</sup>. The higher value associated with Schrödinger's  
221 pyroclastic unit demonstrates that it has a higher cohesion and capacity for added mass, meaning the



222 trafficability for a robotic rover is likely sufficient (Venturino et al., 2016). This is important, as ~15%  
223 and ~30% of the proposed short and long traverses are located within the pyroclastic deposits.  
224 However, there is some uncertainty in these calculations. For example, the reported internal friction  
225 angles derived from boulder tracks range considerably between previous studies (10-50°; Moore, 1970;  
226 Mitchell et al., 1973). It is also not clear to what extent the Apollo 17 orange glass soil density is  
227 representative of the pyroclastic material within Schrödinger. Our calculations also do not take the  
228 effect of the local slope on Terzaghi's bearing capacity equation for circular footings into account. If  
229 HERACLES is pursued, then this issue will need to be examined further.

230

#### 231 *4.4 Sample mass considerations*

232 For the traverses proposed in this study, we assume an arbitrary sample mass of 10 kg per landing.  
233 However, the sample mass that can be returned will depend on the payload capability of the ascent  
234 vehicle. Assessment of the payload capability of a possible ascent vehicle suggests it is likely that >10  
235 kg of sample mass can be accommodated (the Appendix). Another constraint on returned sample  
236 mass is the storage capability of the considered sample containers that are required for sample  
237 transfer between the ascent vehicle and the eDSH.

238 Calculations assuming a prototype spherical sample container (Pratt et al., 2014) suggests total  
239 sample masses can exceed 30 kg (the Appendix). The assumed 30 kg of total sample mass is,  
240 therefore, a baseline. A greater mass of representative returned samples would significantly increase  
241 the productivity of a robotic exploration mission in Schrödinger basin. These additional samples could  
242 be collected from a wide range of identified in-situ stations along both traverses. The size of sample  
243 collected at each station in the concept study is dependent on the type of lithology involved and is  
244 based on recommendations from the Curation and Analysis Planning Team for Extraterrestrial  
245 Materials (CAPTEM) (Shearer et al., 2007).

246

#### 247 **5. Sampling key units within Schrödinger basin**

248 A significant number of key lithological units are present within the Schrödinger basin and sampling  
249 these units will address a wide range of scientific goals defined by the NRC (2007). These units include  
250 SPA-derived material and Schrödinger impact melt, crustal lithologies, secondary impactor material,  
251 and volcanic deposits (pyroclastic and mare) (Fig. 1, 2). Hurwitz and Kring (2015) showed that the  
252 southern basin wall of Schrödinger basin is a promising target for sampling SPA-derived material. In  
253 conjunction with samples of Schrödinger impact melt sheet, samples of SPA-derived material can be

254 used to anchor the early Earth-Moon impact flux and basin forming epoch, addressing the top two  
255 science objectives (NRC, 2007). Along the peak ring area, a significant section of the lunar crust is  
256 exposed and includes anorthositic, noritic, and troctolitic lithologies (Fig. 1, 2). Sampling these  
257 lithologies would test models of planetary differentiation and crustal evolution (NRC Goals 2 and 3),  
258 provide ground-truth standards for remote sensing applications, and yield important insights into the  
259 dynamical processes that occur during peak-ring basin forming events (NRC Goal 6). A large number  
260 of secondary craters thought to be related to the formation of Antoniadi crater and Orientale basin  
261 (Fig. 1, 2) have also been identified within the Schrödinger basin. By targeting such secondary craters,  
262 exotic material from different regions of the Moon could be sampled and analyzed (NRC Goal 1).  
263 Samples of the mare and pyroclastic volcanic deposits within the Schrödinger basin (Fig 1, 2) provide  
264 insight into their mantle source depths, the delivery mechanism to the surface (NRC Goals 2 and 3),  
265 and lunar thermal evolution (NRC Goal 5). The pyroclastic deposits may also be volatile-rich and  
266 sampling this material would evaluate its ISRU potential. Regolith samples and in-situ analyses will  
267 provide insights into regolith processes and surface weathering on the lunar surface (NRC Goal 7).

268

## 269 **6. Traverses**

270 Two traverses were designed within an ESA-specified total traverse distance of 100 to 300 km. The first  
271 traverse is ~207 km long and is designed to explore the basin interior. The second, longer traverse is  
272 ~291 km long and is designed to explore the region between the basin interior and basin wall.

273

### 274 *6.1 The short traverse*

275 The short traverse is situated within the inner peak ring area of the Schrödinger basin. Sampling  
276 along this traverse would access 6 of the geologic units defined by Kramer et al. (2013) and has the  
277 potential to address a significant number of the NRC (2007) science priorities (Table 2, Fig. 4, 5). The  
278 traverse is ~207 km long and accommodates 50 stations with 18 sampling stations (the Appendix).  
279 The other 32 stations are identified as in-situ analysis stations, that are expected to significantly  
280 contribute to the geological context and, therefore, understanding of the returned samples. The  
281 traverse has been divided into three sections with three landing sites. The first section is based on  
282 Potts et al. (2015), but with a proposed 3 km shift to the north-west for the first landing site. This shift  
283 is required to prevent any contamination of the ascent vehicle activities on the first sample station  
284 (Immer et al., 2011). Stations S1-S9 will be visited in the first section and stations S10-S33 and S34-S50  
285 will be investigated in the second and third leg of the traverse, respectively (the Appendix).

286           Sampling stations S1, S14 and S24 are located within the pyroclastic deposits unit (*Ep*) that is  
287 associated with a pyroclastic vent (Wilhelms et al., 1979; Shoemaker et al., 1994; Gaddis et al., 2003;  
288 Kramer et al., 2013). The deposits are morphologically distinct from the surrounding terrain and their  
289  $M^3$  spectral heterogeneities suggest the deposits are more FeO-rich than the surrounding basin floor  
290 (Kramer et al., 2013). This type of volcanic material was emplaced by a volatile-driven fire fountain  
291 eruption (Rutherford and Papale, 2009; Wetzel et al., 2015; Fig. 6). This is based on the analyses of  
292 presumably similar lunar pyroclastic deposits (e.g., Apollo 17 orange glass) which show a surface  
293 coating that is enriched in highly volatile elements relative to the bulk silicate Moon (Meyer et al.,  
294 1975). This is thought to be the result of deposition of volatile-rich vapors onto the glass beads during  
295 cooling of the volcanic gas clouds that envelop the beads (Hauri et al., 2015; Fig. 6). Previous studies  
296 have suggested the pyroclastic volcanism within Schrödinger basin occurred <2 Ga ago, which is  
297 relatively recent (Shoemaker et al., 1994) compared with the inferred age range of ~4.0-1.2 Ga of  
298 mare magmatism on the Moon (Hiesinger et al., 2011). Stations S1, S14 and S14 will provide the first  
299 opportunity to sample pyroclastic material in geological context from the lunar farside. Absolute  
300 dating of these samples will yield an absolute chronology of relatively young lunar processes and,  
301 therefore, will additionally constrain the lunar thermal evolution (NRC Goal 5). Samples of this  
302 material would also provide insights into the compositional evolution of the lunar interior (NRC Goals  
303 2, 3, and 5) by determination of their source depth, formation mechanism, and ISRU potential (Kring,  
304 2014; Kring et al., 2014). The results from in-situ analyses at stations S9-S13 and S15-S26 will provide  
305 insights into the vertical and lateral variability of the pyroclastic deposits, and can be used to further  
306 constrain its compositional variability and distribution (NRC Goal 2, 3 and 5).

307

308

Fig. 4, 5

309

310           After station S1, the traverse continues along the pre-Nectarian peak ring (*pNpr*), where stations S2,  
311 S3 and S5 will sample lithologically distinct boulders derived from the peak ring (Fig. 5a, b). Spectral  
312 observations from the Kaguya spacecraft and the  $M^3$  instrument indicate the presence of anorthositic,  
313 noritic, and troctolitic lithologies at the peak ring (Kramer et al., 2013) (Fig. 1). This suggests that the  
314 peak ring material is composed of pre-Nectarian deep crust, and possibly upper mantle material,  
315 uplifted during the basin forming event (Kramer et al., 2013; Fig. 2). The anorthositic unit is interpreted  
316 to be crystalline material that has not been significantly shocked or melted, representative of pre-impact  
317 crustal material. This is derived from (1) the unmistakable spectral signature of pure anorthosite and (2)

318 the estimated exhumation depth of the peak ring that exceeds the thickness of cumulative ejecta from  
319 all observable ancient basins in proximity to Schrödinger basin (Kramer et al., 2013). The troctolitic unit  
320 is likely to reflect lower crustal material or potentially entrained upper mantle material and may provide  
321 information of the pre-uplift depth, estimated to be 20-30 km (Kring et al., 2013). The eastern part of  
322 the peak ring is well covered by M<sup>3</sup> spectral reflectance data and is in close proximity to the pyroclastic  
323 vent, providing an opportunity for maximizing the science and exploration potential in a relatively small  
324 area (Bunte et al., 2011; O'Sullivan et al., 2011; Potts et al., 2015). The identification of boulders and  
325 associated trails allows for sampling of peak material at slopes accessible to conventional rover designs  
326 (Potts et al., 2015) and will yield the first in-context samples of pristine middle and lower lunar crustal  
327 lithologies.

328 This will test models of planetary differentiation and crustal evolution, therefore addressing the  
329 majority of the science priorities within NRC (2007) Goals 2 and 3. It will also yield insights into the  
330 dynamical processes that occur during peak ring basin forming events (NRC Goal 6) and provide ground-  
331 truth standards to test and refine interpretations based on remote sensing spectral data. In-situ analysis  
332 station S4 on pre-Nectarian peak ring material will provide additional insights into the vertical and  
333 lateral diversity of primitive, lunar crust. Because the competing models for peak ring formation (cf.  
334 Grieve and Cintala 1998 and Kring et al., 2013  
335 <http://www.hou.usra.edu/meetings/lpsc2016/pdf/1659.pdf>) assume different strengths for the material  
336 in peak rings, it will be important to produce high-resolution images of any peak-ring outcrops and  
337 boulders from those outcrops along the traverse.

338 Station S6 will involve the collection of a rake sample and is located close to the fracture north of  
339 the peak ring, where detailed imaging of the cliff wall will provide a regional geological cross section (Fig.  
340 5b, c). In-situ analysis at station S7 and sampling at station S8 will study impact melt breccias from the  
341 inter-peak ring floor material (*lipr*) unit, which is thought to contain peak ring material and Schrödinger  
342 impact melt (Shoemaker et al., 1994; Kramer et al., 2013). This would be the first opportunity to explore  
343 and sample the top of an impact melt sheet on the Moon. Compositional spectra (M<sup>3</sup>) suggest the  
344 dominant composition of the upper portion of the melt sheet is noritic (Kramer et al., 2013). This may  
345 imply that the Schrödinger melt sheet differentiated during cooling, which is a topic of ongoing debate  
346 (e.g., Vaughan et al., 2013). Samples of the excavated floor material within Schrödinger basin could  
347 therefore be used to determine to what extent the melt sheet has differentiated (NRC Goal 6) and  
348 would greatly enhance our ability to interpret Apollo samples. The S6 samples would also provide the

349 age of the Schrödinger impact event and, therefore, constrain the end of the basin-forming epoch (NRC  
350 Goal 1).

351 A number of in-situ analysis stations (S27-S30, S34-S36, S41-S44, S48-S50) and sampling stations  
352 (S32, S37, S38, S45-S49) are situated within the inner-peak ring smooth floor material (*Isip*), where the  
353 rover will sample and analyze additional Schrödinger melt sheet material. This will provide insights into  
354 the vertical and lateral variability of the Schrödinger melt sheet (NRC Goal 6).

355 The rover then continues to stations S31 and S33 where it will sample a relatively smooth and  
356 spectrally FeO-rich unit, previously identified as mare basalt deposits (*Em*) (Shoemaker et al., 1994;  
357 Kramer et al., 2013). At stations S39 and S40, the rover will use in-situ analyses to further study the  
358 mare deposits. It is also likely that at stations S34, S37, S38, S41- S43, presumably inner-peak ring  
359 smooth floor material (*Isip*), additional mare material can be sampled and/or analyzed. The lateral  
360 distribution of the latter sampling and in-situ analysis stations allows for studying melt sheet processes  
361 and the lateral compositional and structural variability of the melt sheet (NRC Goal 6). They will also  
362 further constrain the compositional variability of the mare deposits (NRC Goal 2, 3 and 5). The first in-  
363 context mare basalt samples from the farside will provide insights into the nearside-farside dichotomy  
364 of the lunar surface and could test vital aspects of the lunar magma ocean (LMO) hypothesis, including  
365 cumulate overturn and the lateral and vertical extent of the LMO. They will also provide insight into  
366 their mantle source depths and delivery mechanism to the surface (NRC Goals 2, 3 and 5).

367

368

Fig. 6, 7

369

370 At stations S45-47 the rover will obtain three rake samples near two large secondary craters that  
371 have been identified to originate from Antoniadi crater and Orientale basin (Shoemaker et al., 1994;  
372 Kramer et al., 2013) (Fig. 1b, 2). The physics of ballistic sedimentation suggest that secondary ejecta  
373 deposits mostly consist of reworked target material (Oberbeck et al., 1975). In order to assess the  
374 likelihood of sampling exotic material within the secondary craters identified along the traverse, the  
375 model of Morrison and Oberbeck (1978) was used to calculate the diameter and velocity of ejecta  
376 fragments that created the secondary craters in Schrödinger basin, assuming a 45 degree launch angle.  
377 For a secondary crater of a given diameter, the ratio of surviving primary material to reworked target  
378 material within the ejecta deposit was calculated (Fig. 7). The size-velocity distribution indicates that the  
379 fragments that formed the largest secondary craters in Schrödinger were kilometer-scale blocks moving  
380 at approximately 0.8-2 km/s. At these velocities, it is expected that approximately 5-18% of primary

381 Antoniadi material would survive, whereas <5% of primary Orientale material would have survived (Fig.  
382 7). Sampling this material has the potential to provide highland material, derived from the Orientale  
383 basin, and possibly SPA material, derived from Antoniadi crater (O’Sullivan et al., 2011) (NRC Goal 1).

384 The traverse then continues along a sinuous rill that is likely associated with the mare volcanism  
385 within Schrödinger (Kramer et al., 2013) and a high FeO bluff thought be of volcanic origin (Shoemaker  
386 et al., 1994). Sampling at stations S48 and S49, and in-situ analysis at station S50, will provide insights  
387 into the nature of these features and can be used to determine the compositional and lateral variability  
388 of volcanic deposits within Schrödinger basin (NRC Goal 2, 3 and 5).

389 At a significant number of stations along both traverses, the rover will sample and/or analyze  
390 regolith. These results can be used to address three of the four scientific objectives within NRC (2007)  
391 Goal 7. The majority of primary craters along the short traverse are of Eratosthenian or Copernican age  
392 based on qualitative assessment of crater degradation (Trask, 1971; the Appendix). These craters could  
393 be sampled to more precisely determine the lunar impact flux through time (NRC Goal 1).

394 The estimated total collected sample mass from the short traverse is ~28.5 kg and will address 21  
395 individual investigations identified by NRC (2007), corresponding to 68% of the remaining objectives. If  
396 the experimental package deployed from the second and/or third ascent vehicle landing includes a  
397 seismometer, the lunar interior structure and crater formation processes could also be explored (NRC  
398 Goal 1 and 6). Sampling and in-situ stations for the short traverse are summarized the Appendix.

399 The short traverse can be completed in ~3.5 months, assuming the rover is continuously operated  
400 during lunar days with a constant rover speed of 0.36 km/hr during traversing and without repeated  
401 analyses at sampling or in-situ stations (Table 2). If the number of in-situ analyses at each station is  
402 extended to three analyses per type of in-situ analysis it would take the rover ~6 months to complete  
403 the traverse. This would correspond to a 90% and 83% time margin on the total 3 year mission duration.  
404 If the landings and ascents were scheduled on a fixed 12 month cadence, the traverse can be completed  
405 in ~25 months, providing a 30% margin on schedule. Three in-situ analyses per type of in-situ analysis at  
406 each station would increase the total traverse time to ~26.5 months, corresponding to a 27% margin.

407

## 408 *6.2 Long traverse*

409 The long traverse encompasses both the inner- and outer-peak ring zone of Schrödinger basin and  
410 also traverses 6 geological terrains (Fig. 8, 9). It measures ~291 km in length and includes 66 stations  
411 (including the stations near the southern basin wall proposed by Hurwitz and Kring, 2015). Samples

412 would be collected at 16 of these stations. The other stations are in-situ analysis stations that are  
413 required to provide sufficient geological context for the returned samples (the Appendix).

414 Stations S1-S14 and landing site 1 of the long traverse are identical to the short traverse and will,  
415 thus, sample the three spectrally distinct crustal lithologies from the peak ring (S2, S3, S5), Schrödinger  
416 melt sheet material (S8) and pyroclastic material (S1, S14). In-situ analyses will be performed on peak  
417 ring lithologies (stations S4, S6) and pyroclastic material (stations S9-S13, L1-L2) and will help to  
418 constrain the lateral variability of pristine lunar crustal material and pyroclastic material.

419 In the south the traverse crosses inner-peak ring smooth floor material (*isip*), a zone of secondary  
420 crater fields associated with Orientale basin (*isc*) and smooth outer-peak ring floor material (*isop*)  
421 (Kramer et al., 2013). The rover will perform in-situ analyses on smooth inner-peak ring floor material at  
422 stations L6-L8 and will characterize the existence and lateral extent of melt sheet differentiation (NRC  
423 Goal 6). Sampling stations L12A/L12B, L25 and L30 are located within the secondary crater field and  
424 provide the opportunity to sample surviving exotic material from Antoniadi crater and/or Orientale  
425 basin (Kramer et al., 2013; Fig. 7). Additional in-situ analyses will be performed (Stations L3-L5, L9-L15,  
426 L21-L25, L26-32, L37-L38) along the traverse to additionally constrain the occurrence and composition of  
427 exotic material within Schrödinger basin. The lateral and vertical distribution of stations along this area  
428 is suitable for determining the extent of lateral and vertical mixing of local and ejecta material (NRC Goal  
429 6). In-situ analyses at these stations can also be used to constrain the composition of the underlying  
430 smooth outer-peak ring floor material (*isop*), providing insights into the lateral and compositional  
431 variability of Schrödinger melt sheet and, therefore, in melt sheet processes (NRC Goal 6). Samples from  
432 stations L12A/L12B, L25 and L30 will also provide an absolute age of the Schrödinger impact event (NRC  
433 Goal 1).

434 Sampling stations L16 and L19 are located near the wall slump in the south-eastern part of the peak  
435 ring. Coverage of M<sup>3</sup> data suggests the presence of olivine-bearing, pyroxene-bearing and anorthositic  
436 lithologies. Sampling at these stations combined with in-situ analyses (Stations L17, L18 and L20) will  
437 provide additional insights into the lateral and vertical variability of the lunar crust within the  
438 Schrödinger basin (NRC Goals 2 and 3).

439 In the third section of the long traverse, the rover will have an opportunity to study the smooth  
440 hummocky floor material unit (*ish*) (Stations L33-L41, L50, L51) identified as the most Mg-rich norite  
441 floor unit within Schrödinger (Kramer et al., 2013). This will provide insights into the compositional  
442 range of the Schrödinger melt sheet and the occurrence and/or extent of melt sheet differentiation  
443 (NRC Goal 6).

444 Close to the final landing site, there will be an opportunity to sample material from the southern  
445 wall (*lw*) (stations L45, L46, L47 as suggested by Hurwitz and Kring (2015), or alternatively, stations L43,  
446 L44, L46 and L48 based on this study). A recent study of Hurwitz and Kring (2015) suggest the FeO-rich  
447 signature that is thought to represent an SPA impact melt component in Schrödinger wall outcrops and  
448 floor material extends from the eastern to the south-eastern wall of Schrödinger basin, with estimates  
449 up to 6-8% of SPA material. Compositional  $M^3$  spectra of low-Ca pyroxene in the southern basin wall has  
450 been interpreted to indicate the material has a noritic composition (Kramer et al., 2013).

451 Sampling SPA material would provide an age of the SPA basin-forming event and, therefore, would  
452 anchor the early Earth-Moon impact flux (NRC Goal 1). The results from in-situ analysis stations L38-L42  
453 and L49 will be used to additionally constrain the composition of SPA material and to provide geological  
454 context of the returned samples. Analyses of regolith along the base of the southern wall could also  
455 shed light on the physical properties of ancient regolith (NRC Goal 7).

456 Crater degradation states of >10m craters along the traverse suggest the majority are of  
457 Eratosthenian and Copernican age using the qualitative descriptions of Trask (1971) (the Appendix).  
458 Samples of this material can be used to additionally constrain the lunar impact flux through time. The  
459 long traverse would collect a total sample mass of 29.5 kg (the Appendix) and can address a significant  
460 amount (65%) of the remaining individual investigations identified in the NRC (2007) report.

461 Using the ConOps from Table 2 it is expected that the traverse can be completed within ~5.5  
462 months, which allows for one GRS, APXS and MI analysis and one panorama view at each station.  
463 Repeating the latter analyses three times at each station would extend total traverse time to ~7 months,  
464 providing 85% and 80% margin on both traverse times relative to a 3 year mission duration. If the  
465 landings and ascents were scheduled on a fixed 12 month cadence, the traverse can be completed in  
466 ~26 months, providing 28% margin. The total traverse time is increased to ~27 months if each analysis is  
467 repeated 3 times, corresponding to a 25% margin on the total 3 year mission duration.

468

469

Fig. 8, 9

470

## 471 **7. Future work**

472 Future studies should include a solar irradiance study of Schrödinger basin to aid with determining  
473 optimal mission start dates and to further constrain the times necessary to complete each traverse. This  
474 would be especially important along the south-eastern portion of the peak ring. When rover  
475 specifications have been confirmed, the rover capabilities (e.g., speed, need to hibernate, and



476 communication data rates) and instrumentation payload should be reassessed. The effect of these  
477 changes on ConOps times should then be taken into account to further evaluate traverse times.

478 Several bench craters have been identified along the traverse, which would aid in estimation of  
479 the regolith thickness along the traverses. A TiO<sub>2</sub> map would be useful to investigate the nature of the  
480 pyroclastic and mare deposits in more detail. The traverses proposed in this study have unique subset  
481 routes and, therefore, address different objectives and the possibility of combining both traverses  
482 should be assessed given the time margin for completing the latter traverses.

483

## 484 **8. Conclusions**

485 It has been shown that a long duration, human-assisted robotic mission to the Schrödinger basin can  
486 address all 7 of the remaining lunar science concepts as determined by the NRC (2007). Two robotic  
487 traverses with sample return capabilities within Schrödinger basin have been constructed for a 3 year  
488 mission duration within the HERACLES mission architecture (Landgraf et al., 2015). Both the short- (~207  
489 km) and long (~291 km) traverse accomplish many of the same objectives, but subsets of each traverse  
490 are also unique and, therefore, will address different scientific objectives. The trafficability of the  
491 Schrödinger pyroclastic deposits was assessed and suggests the vent could be explored for ISRU  
492 potential. The proposed traverses would address the majority (>61-65%) of the individual investigations  
493 identified in the NRC (2007) report. Notional ConOps suggests the short and long traverse can be  
494 completed within ~3 and ~5.5 months , providing a ~91% and ~85% margin relative to a 3 year mission  
495 duration. If the landings and ascents were scheduled on a fixed 12 month cadence, the short and long  
496 traverses are expected to be completed within ~24.5 and ~26 months, giving a margin of ~32% and  
497 ~28%. The selected sample stations and notional ConOps suggest both traverses are highly attractive for  
498 long-term robotic exploration of the lunar surface from both a scientific and exploration science point of  
499 view.

500

## 501 **Acknowledgements**

502 This work was carried out through the 2015 Lunar Exploration Summer Intern Program hosted by the  
503 Lunar and Planetary Institute (LPI). This research was supported in part by NASA Solar System  
504 Exploration Research Virtual Institute contract NNA14AB07A (David A. Kring PI). We thank the staff at  
505 LPI for their help and support throughout the internship. LPI Contribution No. ###.

506

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676

## 677 **Figure captions**

678

679 **Fig. 1.** Maps of Schrödinger basin showing (A) the WAC image and (B) the WAC image with overlain  
680 geological map of Kramer et al. (2013) with brown (*Ep*) = pyroclastic material, red (*Em*) = inter-basin  
681 mare material, purple (*Isc*) = secondary crater field, dark purple (*Imp*) = impact melt ponds, from light to  
682 dark blue: *Isip* = smooth inner-peak ring floor material, *Isds* = spectrally distinct smooth floor material,  
683 *Isop* = smooth outer-peak ring floor material, *Ish* = smooth hummocky floor material, *lipr* = inter-peak  
684 ring floor material, *lrh* = rough hummocky floor material, light brown (*lw*) = wall material, horizontally  
685 dashed = wall slump, vertically dashed = peak ring slump and yellow (*pNpr*) = peak ring material.

686

687 **Fig. 2.** Schematic overview of Schrödinger basin showing the major geological units and surface  
688 morphology with a topographic, vertical exaggeration of ~3. Range of pyroclastic source depths based  
689 on Delano (1980), Stolper (1974), Green and Ringwood (1973) and range of mare basalt source depths  
690 based on Walker et al. (1976) and Longhi et al. (1974).

691

692 **Fig. 3.** The identified boulders and trails (detail of NAC images M141351170LE, M141357955LE) within  
693 the pyroclastic material that were used to determine the bearing capacity of the pyroclastic deposits.

694

695 **Fig. 4.** Short traverse. Maps were generated in ArcGIS® using WAC imagery (A) The short traverse  
696 overlain by the geological map of Kramer et al. (2013). The three landing sites are indicated with yellow  
697 filled circles, in-situ analysis stations with open red circles and sampling stations with red filled  
698 circles. Brown (*Ep*) = pyroclastic material, red (*Em*) = inter-basin mare material, purple (*lsc*) = secondary  
699 crater field, light blue (*lrip*) = smooth inner-peak ring floor material, dark blue (*lipr*) = inter-peak ring  
700 floor material and yellow (*pNpr*) = peak ring material. (B) The short traverse overlain by the slope map  
701 based on LOLA data.

702

703 **Fig. 5.** Views along the short traverse. The 3D views were created using LRO NAC images overlain on  
704 LOLA topography data using ArcScene©. (A) Oblique view of the stations along the peak ring area based  
705 on LRO NAC images M108293032LE-RE, M110650294LC-RE, M113006586RC, M167289673LC,  
706 M169650959LC and M174368352RC (B) Boulder identified at station S5. (C) Oblique view of the fracture  
707 north of the peak ring area. (D) Top down view of the fracture at station S6. (E) Station S32 with a ~5 m  
708 boulder, diameter of crater is 220 m.

709

710 **Fig. 6.** Schematic cross-section of the pyroclastic vent in Schrödinger basin based on LOLA topographical  
711 data and surface geological units from Kramer et al. (2013). It shows a volatile-driven fire-fountain type  
712 of eruption, upon which the melt droplets are quenched to glass bead and subsequently coated by  
713 condensation of volatile-rich vapors. Source depth estimates based on Delano (1980), Stolper (1974) and  
714 Green and Ringwood (1973).

715

716 **Fig. 7.** Plot showing the estimated primary material within the secondary ejecta deposit (in wt.%) as a  
717 function of the secondary crater diameter.

718

719 **Fig. 8.** Long traverse. Maps generated in ArcGIS© using WAC imagery. The three landing sites are  
720 indicated with yellow filled circles, in-situ analysis stations with open red circles and sampling stations  
721 with red filled circles. The dashed line is an optional route close to the volcanic vent. (A) The long  
722 traverse overlain by the geological map of Kramer et al. (2013) with brown (*Ep*) = pyroclastic material,  
723 purple (*lsc*) = secondary crater field, from lighter to darker blue: *lrip* = smooth inner-peak ring floor  
724 material, *lipr* = inter-peak ring floor material, *lsh* = smooth hummocky floor material, light brown (*lw*) =  
725 wall material, horizontally dashed = wall slump and yellow (*pNpr*) = peak ring material. (B) The long



726 traverse overlain by the slope map based on LOLA data and corresponding elevation profile of the long  
727 traverse.

728

729 **Fig. 9.** Views from the long traverse. The 3D views were created using LRO NAC images overlain on LOLA  
730 topography data using ArcScene©. (A) View inside the pyroclastic vent from the long traverse. (B-C)  
731 Overview of station L19 showing a ~1.1 km boulder track. The boulder originated from an outcrop  
732 higher up slope. (D) Overview of the SE wall area and the stations identified within this area. (E) The SE  
733 wall area overlain by M<sup>3</sup> data (Kramer et al., 2013). (F) Station L44 showing outcrops of noritic lithologies  
734 based on M<sup>3</sup> data (Kramer et al., 2013). (G) Station L48 situated close to a boulder field of pyroxene-  
735 bearing anorthositic material, based on M<sup>3</sup> data (Kramer et al., 2013).

## APPENDIX A.

**Appendix for “Analyses of Robotic Traverses and Sample Sites in the Schrödinger basin for the HERACLES Human-Assisted Sample Return Mission Concept” by E.S. Steenstra, D.J.P. Martin, F.E. McDonald, S. Paisarnsombat, C. Venturino, S. O’Hara, A. Calzada-Diaz, M.K. Leader, K.K. Klaus, W. van Westrenen, D. H. Needham, D.A. Kring.**

### 1. Details on traverse stations

Tables S.1. and S.2. list the sampling stations that were identified along the short and long traverse, respectively. Included are the location, type of sample and mass, type of in-situ analyses and scientific goals that can be addressed at the identified stations along each traverse. The amount of sampling stations were based on the assumption of a notional baseline of <30 kg of total returned sample mass.

### 2. Calculations of sample mass capabilities of sample container spheres

The maximum sample mass that can be returned from the lunar surface is constrained by the volume of the sample transport container that is required for exchanging the samples from the lander to the exploration Deep Space Habitat (eDSH) and subsequently to the Orion crew vehicle. Current designs include spherical sample containers with variable diameters dependent on their mission context (Pratt et al., 2014). However, the technical specifications (e.g., wall thickness) of these containers are not known. We therefore consider a simple scenario assuming spheres with variable internal diameters and calculate the volumes that would be required for various sample suites (Fig. S.1). Because of the current uncertainty in the sample mass that may be returned to Earth, an arbitrary maximum sample mass of 10 kg per ascent was considered in this study. This is a baseline limit given the lander ascent mass capability presented in this work and additional returned samples would significantly increase the overall productivity of a robotic mission to Schrödinger basin. The different lunar lithologies exhibit a wide range of densities and therefore we assume the associated densities of 3.0-3.3 g/cm<sup>3</sup> for basaltic lithologies (Kiefer et al., 2012), 2.0-2.6 g/cm<sup>3</sup> for impact melt breccias (Warren, 2001; Macke et al., 2012), 1.3-1.8 g/cm<sup>3</sup> for lunar regolith (Mitchell et al., 1972) and 2.6-3.7 g/cm<sup>3</sup> for homogeneous rocks that include anorthosites, norites and dunites. We then calculated the mass capability of the sample container sphere that would be required to accommodate the sampled lithologies along each section of the traverse (Table S.3, Fig. S.1).

### 3. Calculation of ascent vehicle payload capabilities

To assess how much sample mass can be returned from the lunar surface, we designed a baseline, reusable ascent vehicle based on the dimensions of the JPL Mars Ascent Vehicle (MAV). The ascent vehicle has a length of 2.56 meters, a diameter of 0.442 meters, and a mass (with a 30% contingency) of 80 kg (Stephenson and Willenberg, 2006; Dux et al., 2011). A maximum  $\Delta V$  of 2,434 m/s was shown to be sufficient for an ascent vehicle to travel from the lunar surface to Orion in an EM-L2 orbit, EM-L2 halo orbit, or distant retrograde orbit (DRO) (Pratt et al., 2014). The proposed traverses in this study were based notional sample payload of 10 kg per ascent, that has been shown to be the minimum required sample mass that is able to successfully capture important geological samples. We also have shown that this payload is the baseline, and that more returned sample mass would greatly increase the overall productivity of the mission. Four different engines were examined for this ascent vehicle study. Only liquid fuel engines of an appropriate size were selected due to the HERACLES architecture that requires a reusable ascent vehicle. Eqs. (A.1, A.2) were used to calculate the maximum payload for the given  $\Delta V$ :

$$\Delta V = v_e \ln(PMF) \tag{A.1}$$

$$PMF = \frac{Full\ Mass}{Empty\ Mass} \quad (A.2)$$

in which  $\Delta V$  is the change in velocity (m/s),  $V_e$  is the exhaust velocity (m/s) and PMF is the propellant mass fraction. Figure S.2 shows the maximum payload as a function of ascent vehicle volume for each engine type. These calculations suggest the MAV has the ability to lift payload far exceeding 10 kg. Additional calculations were then performed to determine the minimum ascent vehicle engine volume that is required to lift off 10 kg of sample payload from the lunar surface. This requires selection of a certain engine type and type of propellant. The Aestus II, a collaboration between Ottobrunn Space Propulsion Centre and Rocketdyne, seems to be most suited for a reusable ascent vehicle of the size considered in this study. Monomethylhydrazine (MMH) was determined to be the best propellant for storage and refueling due to its relatively high boiling point and low freezing point. Of the engines we considered which use MMH, the Aestus II has the highest ISP and thrust (Table S.4). Propellant storage is also important to consider because of the 3-year mission length of the HERACLES mission concept and the potential for the ascent vehicle to sit on the lunar surface for long periods of time. When the Aestus II engine is considered, we observe that the initial estimate for the size of the ascent vehicle is larger than required for a 11 kg payload (10 kg of samples and 1 kg of packaging). Figure S.3. shows the estimated ascent vehicle dimensions for a wider range of payloads (in this case sample masses).

#### **4. Qualitative assessment of crater degradation states**

Evaluation of the ages of the sampled primary craters along the traverses is essential for determining the recent (post-Imbrian) impact flux. We therefore assessed the age of small (<10 km diameter) primary craters sampled along the traverse using the crater degradation model of Trask (1971). This model is a simple approach that is based on the various degradation states of primary craters due to space weathering over time. We observe that although both traverses will yield samples from relatively young craters, the medium traverse is expected to provide a wider range of sampled crater ages and potentially better calibration of the post-Imbrian impact flux (Fig. S.4.).

#### **5. Soil mechanics and rover trafficability**

Figure S.5. shows the boulder tracks which were used in the calculations related to assessment of rover trafficability in the pyroclastic deposits (see main text). Details on the calculations are provided in Tables S.5-S.7.

#### **6. Communication and returning HD imagery of the lunar surface**

Returning HD imagery is of great importance for the educational and promotional yields of planetary exploration (e.g., the Kaguya mission, Terazono et al., 2009). Here, we assess the possibility of returning HD imagery from the lunar surface to eDSH, and subsequently from the eDSH to ground stations on Earth.

##### *6.1 Communication between rover and eDSH*

Communication between the rover and the eDSH is likely to occur through KA band system, which is currently the most feasible way of communication as there is currently no funding for a dedicated farside communications-relay satellite in an Earth-Moon L2 halo orbit (Pratt et al., 2014). Current mission designs require a high data rate from the rover to the EAM that allows for transmitting high quality (HD) imagery and/or video. However, the data transfer rate between the rover and the EAM may be limited to approximately 200-400 kbps at their average separation distance - approximately ~60,000 km from the lunar surface to the EM-L2 halo orbit (Pratt et al., 2014). Direct transmission of 720p HD video would require ~5 mbps, far exceeding the estimated data transfer rate. High-definition imagery

and/or videos must therefore be transferred at much lower speeds. To determine the feasibility of transmitting stored HD imagery and/or video from the rover, knowledge of the communication data rates during different rover operation modes is required. During traversing, the rover-eDSH communications data rate will be ~89 kbps as it requires continuous operation of the two Hazcams and the Ground Penetrating Radar (Table 1, main text). During stationary analyses, data rates will be significantly lower. For example during APXS analysis, the Hazcams and GPR can be turned off allowing for the transfer of HD imagery and/or videos stored on the rover.

### *6.2 Communication between eDSH and ground stations on Earth*

For the communication between the eDSH and ground stations on Earth we performed a trade study between KA-band or laser communication. Laser communication has heritage on the Laser Lunar Communication Demonstration (LLCD) on the Lunar Atmospheric and Dust Environment Explorer (LADEE) mission, whereas KA-band communication has heritage on many missions (e.g., Kepler, the Lunar Reconnaissance Orbiter and military satellites). However, improvements in laser communication has been identified as an important technology development for future deep space exploration, because it has the potential to deliver data rates that far exceeds those using KA-band (e.g., Boroson and Robinson, 2014). Laser communication also requires half the power that is used for KA-band (Table S.8.). However, for a robotic mission to the lunar surface the distance between the eDSH and the Earth is insufficiently large for significant delays for KA-band communication. In addition, clouds may have a significant effect on laser communication. For example, thin cloud coverage can potentially reduce the data rate to 77 Mbps (Cornwell et al., 2014). The use of laser communication would also require more ground stations on Earth's than currently available. We conclude that, given the amount of data that would need to be transferred to support HD imagery and the heritage of both types of communication, KA-band is sufficient and less costly for communication between the eDSH and ground stations on Earth.

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**Table S.1.** Summary of location, type of sample and mass, type of in-situ analyses and scientific goals (NRC, 2007) that can be addressed at the identified stations of the short traverse assuming a notional baseline of <30 kg of total returned sample mass

|                       | Latitude | Longitude | Elevation (m) | Lithological unit <sup>1</sup> | Sample type and mass (g) <sup>2</sup> | Scientific goals addressed <sup>3</sup>                    |
|-----------------------|----------|-----------|---------------|--------------------------------|---------------------------------------|--|
| <b>Landing site 1</b> | -75.4050 | 141.1768  | -4733         |                                |                                       |  |
| <i>Station S1</i>     | -75.4907 | 141.3745  | -4723         | Ep                             | Regolith (2000)                       | 2b, 2d, 5c, 5d, 7b, 7c                                     |
| <i>Station S2</i>     | -75.4906 | 142.0473  | -4541         | pNpr                           | Boulder (500) <sup>a</sup>            | 2a, 3a, 3b, 3c, 3d   |
| <i>Station S3</i>     | -75.3983 | 142.1327  | -4520         | pNpr                           | Boulder (500) <sup>a</sup>            | 2a, 3a, 3b, 3c, 3d   |
| <i>Station S4</i>     | -75.3651 | 142.1738  | -4465         | pNpr                           | Boulder (N/A)                         | 2a, 3a, 3b, 3c, 3d   |
| <i>Station S5</i>     | -75.2628 | 142.2408  | -4506         | pNpr                           | Boulder (500) <sup>a</sup>            | 2a, 3a, 3b, 3c, 3d   |
| <i>Station S6</i>     | -75.1507 | 141.9541  | -4820         | Ep/pNpr                        | Mixed rake (1000)                     | 2a, 2b, 2d, 3a, 3b, 3c, 3d, (4a, 4b, 4c), 5c, 5d           |
| <i>Station S7</i>     | -75.2560 | 141.8327  | -4651         | lipr                           | Boulder (N/A)                         | 6c   |
| <i>Station S8</i>     | -75.3027 | 141.9196  | -4618         | lipr                           | Boulder (5000) <sup>b</sup>           | 1a, 1c, 1d, 6c   |
| <i>Station S9</i>     | -75.4149 | 141.4296  | -4740         | Ep                             | Regolith (N/A)                        | 2b, 2d, 5c, 5d, 7b, 7c                                     |
| <b>Landing site 1</b> | -75.4050 | 141.1768  | -4733         |                                | <b>(Total: 9.5 kg)</b>                |  |
| <i>Station S10</i>    | -75.3602 | 140.9211  | -4706         | Ep                             | Boulder (N/A)                         | 2b, 2d, 5c, 5d, 6c, 6d                                     |
| <i>Station S11</i>    | -75.3370 | 140.8480  | -4734         | Ep                             | Regolith (N/A)                        | 2b, 2d, 5c, 5d, 6c, 6d, 7b, 7c                             |
| <i>Station S12</i>    | -75.3121 | 140.4326  | -4590         | Ep                             | Boulder (N/A)                         | 2b, 2d, 5c, 5d, 6c   |
| <i>Station S13</i>    | -75.2946 | 140.3430  | -4586         | Ep                             | Regolith (N/A)                        | 2b, 2d, 3b, 5c, 5d, 7b, 7c                                 |
| <i>Station S14</i>    | -75.2554 | 140.2323  | -4572         | Ep                             | Regolith (2000)                       | 1d, 2b, 2d, 5c, 5d, 7b, 7c                                 |
| <i>Station S15</i>    | -75.1561 | 140.1177  | -4538         | Ep                             | Boulder (N/A)                         | 2b, 2d, 5c, 5d, 6c   |
| <i>Station S16</i>    | -75.0817 | 140.1110  | -4586         | Ep                             | Boulder (N/A)                         | 2b, 2d, 5c, 5d, 6c   |
| <i>Station S17</i>    | -75.0749 | 140.1027  | -4590         | Ep                             | Regolith (N/A)                        | 2b, 2d, 5c, 5d, 6c, 7b, 7c                                 |
| <i>Station S18</i>    | -75.0287 | 140.2267  | -4634         | Ep                             | Regolith (N/A)                        | 2b, 2d, 5c, 5d, 6c, 7b, 7c                                 |
| <i>Station S19</i>    | -74.9926 | 140.2379  | -4654         | Ep                             | Regolith (N/A)                        | 2b, 2d, 5c, 5d, 6c, 7b, 7c                                 |
| <i>Station S20</i>    | -74.9580 | 140.1913  | -4676         | Ep                             | Regolith (N/A)                        | 2b, 2d, 5c, 5d, 6c, 7b, 7c                                 |
| <i>Station S21</i>    | -74.9087 | 140.0887  | -4746         | Ep                             | Regolith (N/A)                        | 2b, 2d, (4a, 4b, 4c), 5c, 5d, 7b, 7c                       |
| <i>Station S22</i>    | -74.8699 | 139.1497  | -4664         | Ep                             | Regolith (N/A)                        | 2b, 2d, 5c, 5d, 6c, 7b, 7c                                 |
| <i>Station S23</i>    | -74.8453 | 139.0352  | -4660         | Ep                             | Boulder (N/A)                         | 2b, 2d, 5c, 5d, 6c   |
| <i>Station S24</i>    | -74.8570 | 138.7690  | -4650         | Ep                             | Regolith (2000)                       | 1d, 1e, 2b, 2d, 5c, 5d, 6c, 7b, 7c                         |
| <i>Station S25</i>    | -74.7741 | 138.8835  | -4710         | Ep                             | Boulder (N/A)                         | 2b, 2d, 5c, 5d, 6c   |
| <i>Station S26</i>    | -74.5854 | 138.7655  | -4767         | Ep                             | GPR (N/A)                             | 5c, 7b, 7c   |
| <i>Station S27</i>    | -74.5501 | 138.7259  | -4801         | Ep/Isip                        | GPR (N/A)                             | 5c, 7b, 7c   |
| <i>Station S28</i>    | -74.5186 | 138.6371  | -4804         | Ep/Isip                        | GPR (N/A)                             | 5c, 7b, 7c   |
| <i>Station S29</i>    | -74.2082 | 138.1795  | -4821         | Isip                           | Boulder (N/A)                         | 6a, 6c, 6d   |
| <i>Station S30</i>    | -74.1183 | 138.1210  | -4779         | Isip                           | Boulder (N/A)                         | 6a, 6c, 6d   |
| <i>Station S31</i>    | -73.8455 | 137.5857  | -4835         | Em                             | Regolith (500)                        | 2b, 2d, 3a, 3b, 5a, 5b, 5d, 7b, 7c                         |
| <i>Station S32</i>    | -73.9664 | 136.4695  | -4775         | Isip                           | Boulder (5000) <sup>b</sup>           | 1a, 1c, 1e, 6a, 6c, 6d                                     |
| <i>Station S33</i>    | -74.1203 | 134.7569  | -4784         | Em                             | Regolith (500)                        | 2b, 2d, 3a, 3b, 5a, 5b, 5d, 7b, 7c                         |
| <b>Landing site 2</b> | -74.0760 | 134.5498  | -4778         |                                | <b>(Total: 10.0 kg)</b>               |  |
| <i>Station S34</i>    | -74.0478 | 133.8572  | -4776         | Em/Isip                        | Boulder (N/A)                         | 2b, 2d, 3a, 3b, 5a, 5b, 5d                                 |
| <i>Station S35</i>    | -74.0383 | 133.6015  | -4782         | Isip                           | Boulder (N/A)                         | 6a, 6c, 6d   |
| <i>Station S36</i>    | -74.0420 | 133.5345  | -4792         | Isip                           | Boulder (N/A)                         | 6a, 6c, 6d   |
| <i>Station S37</i>    | -74.0455 | 133.5285  | -4796         | Em/Isip                        | Boulder (500)                         | 2b, 2d, 3a, 3b, 5a, 5b, 5d, 6a, 6c, 6d                     |
| <i>Station S38</i>    | -74.0520 | 133.4926  | -4805         | Em/Isip                        | Boulder (500)                         | 2b, 2d, 3a, 3b, 5a, 5b, 5d, 6a, 6c, 6d                     |
| <i>Station S39</i>    | -74.0743 | 133.4241  | -4811         | Em                             | Regolith (N/A)                        | 2b, 2d, 3a, 3b, 5a, 5b, 7b, 7c                             |
| <i>Station S40</i>    | -74.0941 | 133.3957  | -4810         | Em                             | Boulder (N/A)                         | 2b, 2d, 3a, 3b, 5a, 5b                                     |
| <i>Station S41</i>    | -74.1973 | 133.3561  | -4786         | Em/Isip                        | Boulder (N/A)                         | 2b, 2d, 3a, 3b, 5a, 5b, 6a, 6c, 6d                         |
| <i>Station S42</i>    | -74.2370 | 132.9933  | -4775         | Em/Isip                        | Regolith (N/A)                        | 2b, 2d, 3a, 3b, 5a, 5b, 6a, 6c, 6d, 7b, 7c                 |
| <i>Station S43</i>    | -74.2655 | 132.9633  | -4752         | Em/Isip                        | Boulder (N/A)                         | 2b, 2d, 3a, 3b, 6a, 6c, 6d                                 |
| <i>Station S44</i>    | -74.3108 | 132.8374  | -4736         | Isip                           | Boulder (N/A)                         | 6a, 6c, 6d   |
| <i>Station S45</i>    | -74.4394 | 132.9465  | -4673         | Isip                           | Mixed rake (333)                      | 1a, 1c, 1e, 3d, 6a, 6c, 6d                                 |
| <i>Station S46</i>    | -74.4998 | 133.4288  | -4703         | Isip                           | Mixed rake (333)                      | 1a, 1c, 1e, 3d, 6a, 6c, 6d                                 |
| <i>Station S47</i>    | -74.6019 | 133.3457  | -4676         | Isip                           | Mixed rake (333)                      | 1a, 1c, 1e, 3d, 6a, 6c, 6d                                 |
| <i>Station S48</i>    | -74.8181 | 133.4272  | -4642         | Isip                           | Boulder (5000) <sup>b</sup>           | 1a, 1c, 1e, 6a, 6c, 6d                                     |
| <i>Station S49</i>    | -74.9557 | 133.0139  | -4481         | Isip                           | Regolith (2000)                       | 1a, 1c, 2a, 2b, 2d, 3a, 3b, 3c, 3d, 5a, 5b, 5d, 6a, 7b, 7c |
| <i>Station S50</i>    | -75.0866 | 133.3906  | -4595         | Isip                           | Regolith (N/A)                        | 2a, 2b, 2d, 3a, 3b, 3c, 3d, 5a, 5b, 6a, 7b, 7c             |
| <b>Landing site 3</b> | -75.1710 | 133.3401  | -4587         |                                | <b>(Total: 9.0 kg)</b>                |  |
|                       |          |           |               |                                | <b>(Traverse total: 28.5 kg)</b>      |  |

<sup>a</sup>Based on M3 spectra considered to be a crystalline, homogeneous rock (sample mass after Shearer et al., 2007)

<sup>b</sup>Assumed to be heterogeneous impact melt breccia (sample mass after CAPTEM, 2007)

<sup>1</sup>Kramer et al. (2013) <sup>2</sup>Based on CAPTEM recommendations (Shearer et al., 2007) <sup>3</sup>NRC (2007)

**Table S.2.** Summary of location, type of sample and mass, type of in-situ analyses and scientific goals (NRC, 2007) that can be addressed at the identified stations of the long traverse assuming a notional baseline of <30 kg of total returned sample mass

|                       | Latitude | Longitude | Elevation (m) | Lithological unit <sup>1</sup> | Sample type and mass (g) <sup>2</sup> | Scientific goals addressed <sup>3</sup>          |
|-----------------------|----------|-----------|---------------|--------------------------------|---------------------------------------|--|
| <b>Landing site 1</b> | -75.4050 | 141.1768  | -4733         |                                |                                       |  |
| <i>Station S1</i>     | -75.4907 | 141.3745  | -4723         | Ep                             | Regolith (2000)                       | 2b, 2d, 5c, 5d, 7b, 7c                           |
| <i>Station S2</i>     | -75.4906 | 142.0473  | -4541         | pNpr                           | Boulder (500) <sup>a</sup>            | 2a, 3a, 3b, 3c, 3d                               |
| <i>Station S3</i>     | -75.3983 | 142.1327  | -4520         | pNpr                           | Boulder (500) <sup>a</sup>            | 2a, 3a, 3b, 3c, 3d                               |
| <i>Station S4</i>     | -75.3651 | 142.1738  | -4465         | pNpr                           | Boulder (N/A)                         | 2a, 3a, 3b, 3c, 3d                               |
| <i>Station S5</i>     | -75.2628 | 142.2408  | -4506         | pNpr                           | Boulder (500) <sup>a</sup>            | 2a, 3a, 3b, 3c, 3d                               |
| <i>Station S6</i>     | -75.1507 | 141.9541  | -4820         | Ep/pNpr                        | Mixed rake (1000)                     | 2a, 2b, 2d, 3a, 3b, 3c, 3d, (4a, 4b, 4c), 5c, 5d |
| <i>Station S7</i>     | -75.2560 | 141.8327  | -4651         | lipr                           | Boulder (N/A)                         | 6c   |
| <i>Station S8</i>     | -75.3027 | 141.9196  | -4618         | lipr                           | Boulder (5000) <sup>b</sup>           | 1a, 1c, 1d, 6c                                   |
| <i>Station S9</i>     | -75.4149 | 141.4296  | -4740         | Ep                             | Regolith (N/A)                        | 2b, 2d, 5c, 5d, 7b, 7c                           |
| <b>Landing site 1</b> | -75.4050 | 141.1768  | -4733         |                                | <b>(Total: 9.5 kg)</b>                |  |
| <i>Station S10</i>    | -75.3602 | 140.9211  | -4706         | Ep                             | Boulder (N/A)                         | 2b, 2d, 5c, 5d, 6c, 6d                           |
| <i>Station S11</i>    | -75.3370 | 140.8480  | -4734         | Ep                             | Regolith (N/A)                        | 2b, 2d, 5c, 5d, 6c, 6d, 7b, 7c                   |
| <i>Station S12</i>    | -75.3121 | 140.4326  | -4590         | Ep                             | Boulder (N/A)                         | 2b, 2d, 5c, 5d, 6c                               |
| <i>Station S13</i>    | -75.2946 | 140.3430  | -4586         | Ep                             | Regolith (N/A)                        | 2b, 2d, 3b, 5c, 5d, 7b, 7c                       |
| <i>Station S14</i>    | -75.2554 | 140.2323  | -4572         | Ep                             | Regolith (2000)                       | 1d, 2b, 2d, 5c, 5d, 7b, 7c                       |
| <i>Station L1</i>     | -75.3675 | 138.5676  | -4336         | Ep                             | Regolith (N/A)                        | 2b, 2d, 5c, 5d, 7b, 7c                           |
| <i>Station L2</i>     | -75.6870 | 138.6578  | -4745         | Ep                             | Boulder (N/A)                         | 2b, 2d, 5c, 5d, 6c                               |
| <i>Station L3</i>     | -75.7592 | 138.7186  | -4735         | lsc                            | Mixed Rake (N/A)                      | 2b, 2d, 5c, 5d, 6a, 6c, 6d                       |
| <i>Station L4</i>     | -75.7703 | 138.4000  | -4738         | lsc                            | Mixed Rake (N/A)                      | 2b, 2d, 5c, 5d, 6a, 6c, 6d                       |
| <i>Station L5</i>     | -75.8157 | 138.2629  | -4668         | lsc                            | Mixed Rake (N/A)                      | 2b, 2d, 5c, 5d, 6a, 6c, 6d                       |
| <i>Station L6</i>     | -75.8212 | 138.0631  | -4712         | Isip                           | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L7</i>     | -76.0064 | 137.7253  | -4737         | Isip                           | Regolith (N/A)                        | 6a, 6c, 6d, 7b, 7c                               |
| <i>Station L8</i>     | -76.1349 | 137.8276  | -4698         | Isip                           | Regolith (N/A)                        | 6a, 6c, 6d, 7b, 7c                               |
| <i>Station L9</i>     | -76.0830 | 138.2716  | -4692         | lsc                            | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L10</i>    | -76.1640 | 138.8389  | -4706         | lsc                            | Regolith (N/A)                        | 6a, 6c, 6d, 7b, 7c                               |
| <i>Station L11</i>    | -76.3181 | 138.6777  | -4637         | lsc                            | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L12A</i>   | -76.5039 | 138.4047  | -4597         | lsc                            | Boulder (5000) <sup>b</sup>           | 1a, 1c, 1d, 1e, 6a, 6c, 6d                       |
| <i>Station L12B</i>   | -76.5969 | 139.9789  | -4550         | lsc                            | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L13</i>    | -76.7729 | 141.1660  | -4622         | Isop                           | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L14</i>    | -76.7558 | 141.3614  | -4642         | Isop/lsc                       | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L15</i>    | -76.8070 | 141.8635  | -4683         | Isop                           | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L16</i>    | -76.6487 | 142.9195  | -4429         | lw slump                       | Boulder (500)*                        | 2a, 3a, 3b, 3c, 3d                               |
| <i>Station L17</i>    | -76.8625 | 142.7509  | -4722         | lw slump                       | Boulder (N/A)                         | 2a, 3a, 3b, 3c, 3d                               |
| <i>Station L18</i>    | -76.8940 | 142.7962  | -4661         | lw slump                       | Boulder (N/A)                         | 2a, 3a, 3b, 3c, 3d                               |
| <i>Station L19</i>    | -76.9163 | 142.7086  | -4714         | lw slump                       | Boulder (500) <sup>a</sup>            | 2a, 3a, 3b, 3c, 3d                               |
| <i>Station L20</i>    | -76.9627 | 142.5892  | -4716         | Isop/lw slump                  | Boulder (N/A)                         | 2a, 3a, 3b, 3c, 3d                               |
| <i>Station L21</i>    | -77.0552 | 142.6220  | -4686         | Isop                           | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L22</i>    | -77.1993 | 142.6219  | -4688         | Isop                           | Regolith/Boulder (N/A)                | 6a, 6c, 6d, (7b, 7c)                             |
| <i>Station L23</i>    | -77.2073 | 142.5837  | -4685         | lsc/Isop                       | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L24</i>    | -77.3054 | 142.8158  | -4680         | lsc                            | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L25</i>    | -77.3787 | 142.5967  | -4615         | lsc                            | Regolith (2000)                       | 1a, 1b, 1c, 1e, 6a, 6c, 6d, 7b, 7c               |
| <i>Station L26</i>    | -77.4581 | 142.0336  | -4599         | lsc/Isop                       | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <b>Landing site 2</b> | -77.4732 | 141.8233  | -4597         |                                | <b>(Total: 10.0 kg)</b>               |  |
| <i>Station L27</i>    | -77.5210 | 142.1097  | -4630         | Isop                           | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L28</i>    | -77.6336 | 142.0954  | -4622         | Isop                           | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L29</i>    | -77.6596 | 142.0155  | -4609         | Isop/lsc                       | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L30</i>    | -77.7209 | 142.4214  | -4628         | Isop                           | Mixed Rake (1000)                     | 1a, 1b, 1c, 1e, 6a, 6c, 6d                       |
| <i>Station L31</i>    | -77.8093 | 142.1883  | -4605         | Isop/lsc                       | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L32</i>    | -77.8770 | 142.2026  | -4609         | lsc/Isop                       | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L33</i>    | -78.0937 | 142.0777  | -4608         | Ish                            | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L34</i>    | -78.0927 | 142.0508  | -4609         | Ish                            | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L35</i>    | -78.0954 | 142.0484  | -4607         | Ish                            | Regolith (N/A)                        | 7b, 7c   |
| <i>Station L36</i>    | -78.1133 | 141.6494  | -4571         | Ish                            | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L37</i>    | -78.3246 | 142.5125  | -4617         | lsc                            | Boulder (N/A)                         | 6a, 6c, 6d                                       |
| <i>Station L38</i>    | -78.4942 | 142.3218  | -4615         | Ish/lw/lsc                     | Boulder (N/A)                         | 2a, 3a, 3b, 3c, 3d, 6a, 6c, 6d                   |
| <i>Station L39</i>    | -78.5627 | 141.5129  | -4521         | lw/Ish                         | Boulder (N/A)                         | 2a, 3a, 3b, 3c, 3d, 6a, 6c, 6d                   |
| <i>Station L40</i>    | -78.5974 | 141.1479  | -4489         | lw/Ish                         | Boulder (N/A)                         | 2a, 3a, 3b, 3c, 3d, 6a, 6c, 6d                   |
| <i>Station L41</i>    | -78.6726 | 141.0683  | -4375         | lw/Ish                         | Boulder (N/A)                         | 2a, 3a, 3b, 3c, 3d, 6a, 6c, 6d                   |

|                               |          |          |       |        |                                  |  |
|-------------------------------|----------|----------|-------|--------|----------------------------------|--|
| Station L42                   | -78.7209 | 140.8983 | -4309 | lw     | Boulder (N/A)                    | 2a, 3a, 3b, 3c, 3d                             |
| Station L43 <sup>d</sup>      | -78.9803 | 139.8941 | -4164 | lw     | Mixed Rake (1000)                | 1a, 1b, 1c, 1e, 2a, 3a, 3b, 3c, 3d, 6a, 6c, 6d |
| Station L44 <sup>d</sup>      | -79.1208 | 140.0125 | -3548 | lw     | Boulder (5000) <sup>b</sup>      | 1a, 1b, 1c, 1e, 2a, 3a, 3b, 3c, 3d             |
| ALT: Station L45 <sup>e</sup> | -79.1203 | 139.0837 | -3607 | lw     | Mixed Rake (1000)                | 1a, 1b, 1c, 1e, 2a, 3a, 3b, 3c, 3d             |
| ALT: Station L46 <sup>e</sup> | -79.1515 | 139.0631 | -3224 | lw     | Boulder (5000) <sup>b</sup>      | 1a, 1b, 1c, 1e, 2a, 3a, 3b, 3c, 3d             |
| ALT: Station L47 <sup>e</sup> | -78.1885 | 139.0997 | -2736 | lw     | Mixed Rake (1000)                | 1a, 1b, 1c, 1e, 2a, 3a, 3b, 3c, 3d             |
| Station L48 <sup>d</sup>      | -78.9845 | 139.5554 | -4177 | lw/lsh | Mixed Rake (1000)                | 1a, 1b, 1c, 1e, 2a, 3a, 3b, 3c, 3d, 6a, 6c, 6d |
| Station L49                   | -78.9254 | 139.6857 | -4220 | lw     | Boulder (N/A)                    | 2a, 3a, 3b, 3c, 3d, 6a, 6c, 6d                 |
| Station L50                   | -78.8769 | 139.6190 | -4318 | lsh    | Boulder (N/A)                    | 2a, 3a, 3b, 3c, 3d                             |
| Station L51                   | -78.6734 | 139.5241 | -4311 | lsh    | Regolith (2000)                  | 1a, 1b, 1c, 6a, 6d, 7b, 7c                     |
| <b>Landing Site 3</b>         | -78.6619 | 139.5242 | -4314 |        | <b>(Total: 10 kg)</b>            |  |
|                               |          |          |       |        | <b>(Traverse total: 29.5 kg)</b> |  |

<sup>a</sup>Based on M3 spectra considered to be a crystalline, homogeneous rock (sample mass after Shearer et al., 2007)

<sup>b</sup>Assumed to be heterogeneous impact melt breccia (sample mass after CAPTEM, 2007)

<sup>1</sup>Kramer et al. (2013) <sup>2</sup>Based on CAPTEM recommendations (Shearer et al., 2007) <sup>3</sup>NRC (2007) <sup>4</sup>Proposed sites from this study to sample SPA material <sup>5</sup>Alternative sites for sampling SPA material based on Hurwitz and Kring (2015)

**Table S.3.** The collected lithologies and their relative abundances during each section of the short and long traverse based on CAPTEM recommendations (Shearer et al., 2007).

|                       | Basalt | Impact breccia | Regolith | Homogeneous <sup>a</sup> |
|-----------------------|--------|----------------|----------|--------------------------|
| <b>Short traverse</b> |        |                |          |                          |
| Section 1             | 0.0    | 0.6            | 0.2      | 0.2                      |
| Section 2             | 0.1    | 0.5            | 0.4      | 0.0                      |
| Section 3             | 0.1    | 0.7            | 0.2      | 0.0                      |
| <b>Long traverse</b>  |        |                |          |                          |
| Section 1             | 0.0    | 0.6            | 0.2      | 0.2                      |
| Section 2             | 0.0    | 0.7            | 0.2      | 0.1                      |
| Section 3             | 0.0    | 0.8            | 0.2      | 0.0                      |

<sup>a</sup>Homogeneous rocks include anorthosites, norites and dunites.

**Table S.4.** Properties of each engine type.

|                                      | Aestus | Aestus II | AJ-10       | R-40B  |
|--------------------------------------|--------|-----------|-------------|--------|
| <b>Propellant type</b>               | MMH    | MMH       | Aerozine 50 | MMH    |
| <b>Oxidizer</b>                      | NTO    | NTO       | NTO         | NTO    |
| <b>Propellant boiling point (F)</b>  | 190    | 190       | 158         | 190    |
| <b>Propellant freezing point (F)</b> | -62.3  | -62.3     | 19.4        | -62.3  |
| <b>ISP (s)</b>                       | 324    | 340       | 319         | 293    |
| <b>Thrust (N)</b>                    | 29600  | 55400     | 43700       | 4000   |
| <b>Dry mass (kg)</b>                 | 111 kg | 138 kg    | 100 kg      | 6.8 kg |

**Table S.5.** Boulder locations and properties that were used to assess the bearing capacity of the pyroclastic material.

| Boulder  | Latitude | Longitude | Boulder Radius (cm) | Radius at Surface (cm) | Track Width (m) | Track Length (m) | Slope (°) | Track Depth (cm) |
|----------|----------|-----------|---------------------|------------------------|-----------------|------------------|-----------|------------------|
| <b>1</b> | -75.156  | 140.118   | 297.5               | 275                    | 4.14            | 120              | 2-4       | 183              |
| <b>2</b> | -75.163  | 140.131   | 259                 | 251                    | 3.68            | 98               | 2-4       | 195              |
| <b>3</b> | -75.309  | 139.173   | 544.5               | 521                    | 6.5             | 356              | 10-12     | 387              |



**Table S.6.** Calculations of the bearing capacity (dynes/cm<sup>2</sup>) of the pyroclastic material for an assumed internal friction angle of 30°.

| Boulder        | Soil Density = 2 g/cm <sup>2</sup>        |                                       | Soil Density = 2.29 g/cm <sup>2</sup>     |                                       |
|----------------|---|---------------------------------------|---|---------------------------------------|
|                | Bearing Capacity (dynes/cm <sup>2</sup> ) | Bearing Capacity (kN/m <sup>2</sup> ) | Bearing Capacity (dynes/cm <sup>2</sup> ) | Bearing Capacity (kN/m <sup>2</sup> ) |
| 1              | 2.60 x 10 <sup>6</sup>                    | 2.57 x 10 <sup>5</sup>                | 2.80 x 10 <sup>6</sup>                    | 2.80 x 10 <sup>5</sup>                |
| 2              | 2.59 x 10 <sup>6</sup>                    | 2.59 x 10 <sup>5</sup>                | 2.81 x 10 <sup>6</sup>                    | 2.81 x 10 <sup>5</sup>                |
| 3              | 5.19 x 10 <sup>6</sup>                    | 5.19 x 10 <sup>5</sup>                | 5.62 x 10 <sup>6</sup>                    | 5.62 x 10 <sup>5</sup>                |
| <b>Average</b> | 3.46 x 10 <sup>6</sup>                    | 3.45 x 10 <sup>5</sup>                | 3.74 x 10 <sup>6</sup>                    | 3.74 x 10 <sup>5</sup>                |

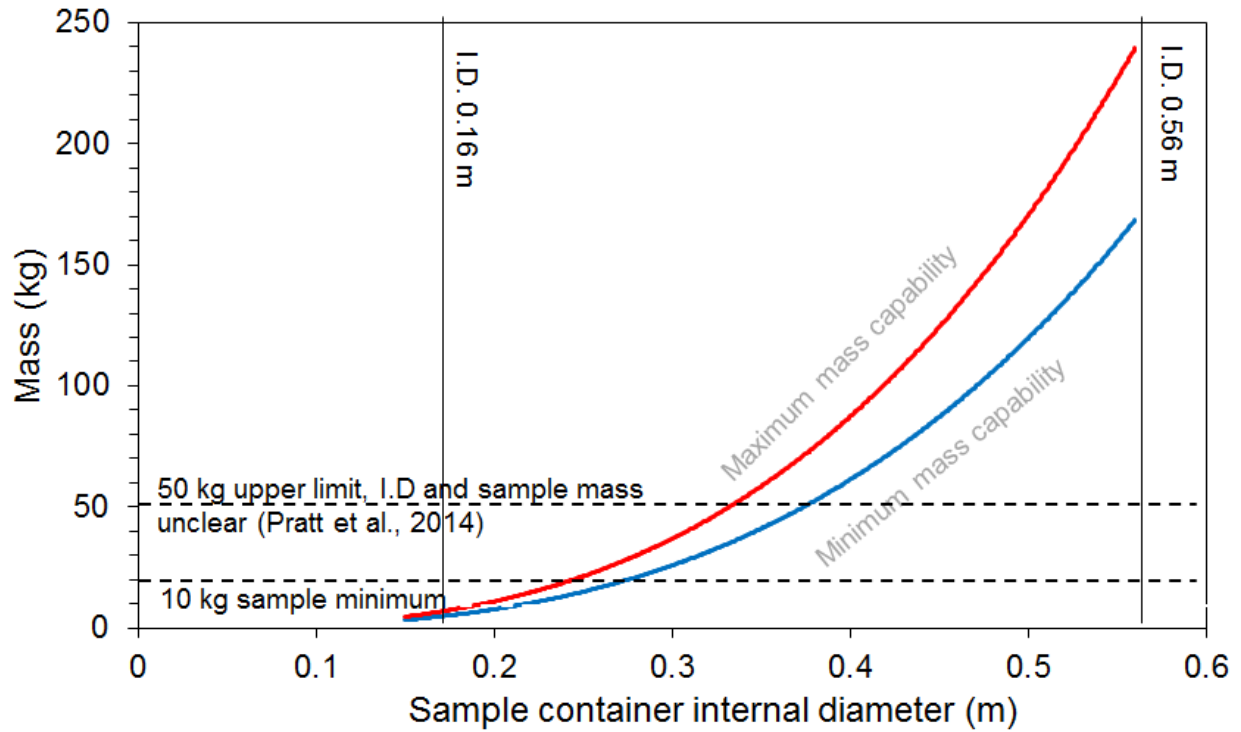
**Table S.7.** Calculations of the bearing capacity (dynes/cm<sup>2</sup>) of the pyroclastic material for an assumed internal friction angle of 35°.

| Boulder        | Soil Density = 2 g/cm <sup>2</sup>        |                                       | Soil Density = 2.29 g/cm <sup>2</sup>     |                                       |
|----------------|---|---------------------------------------|---|---------------------------------------|
|                | Bearing Capacity (dynes/cm <sup>2</sup> ) | Bearing Capacity (kN/m <sup>2</sup> ) | Bearing Capacity (dynes/cm <sup>2</sup> ) | Bearing Capacity (kN/m <sup>2</sup> ) |
| 1              | 4.82 x 10 <sup>6</sup>                    | 4.82 x 10 <sup>5</sup>                | 5.18 x 10 <sup>6</sup>                    | 5.18 x 10 <sup>5</sup>                |
| 2              | 4.79 x 10 <sup>6</sup>                    | 4.79 x 10 <sup>5</sup>                | 5.17 x 10 <sup>6</sup>                    | 5.17 x 10 <sup>5</sup>                |
| 3              | 9.62 x 10 <sup>6</sup>                    | 9.62 x 10 <sup>5</sup>                | 1.04 x 10 <sup>7</sup>                    | 1.04 x 10 <sup>6</sup>                |
| <b>Average</b> | 6.41 x 10 <sup>6</sup>                    | 6.41 x 10 <sup>5</sup>                | 6.91 x 10 <sup>6</sup>                    | 6.91 x 10 <sup>5</sup>                |

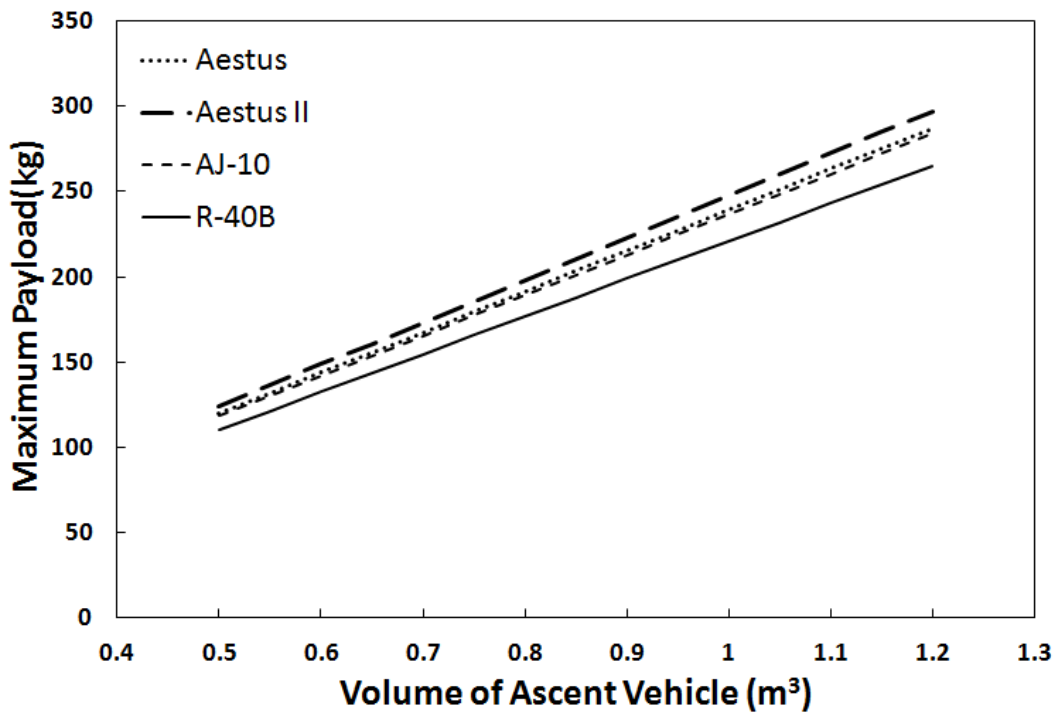
**Table S.8.** Summary of trade study between KA-band and laser communication.

|   | KA-band                  | Laser             |
|---|--------------------------|-------------------|
| Data rate                                       | 5-100 Mbps               | Up to 600 Mbps    |
| Bandwidth                                       | 32 GHz                   | 300,000 GHz       |
| Power   |                          | Half of KA-band   |
| Heritage  | >15 missions             | LLCD              |
| Earth weather impact                            | No                       | Yes               |
| No. of ground stations required                 | Currently >4, sufficient | Additional needed |
| Forward application for Mars                    | No, currently in use     | Yes               |
| Download time for "Apollo 13" movie (36.000 MB) | 49.1 minutes             | 7.9 minutes       |

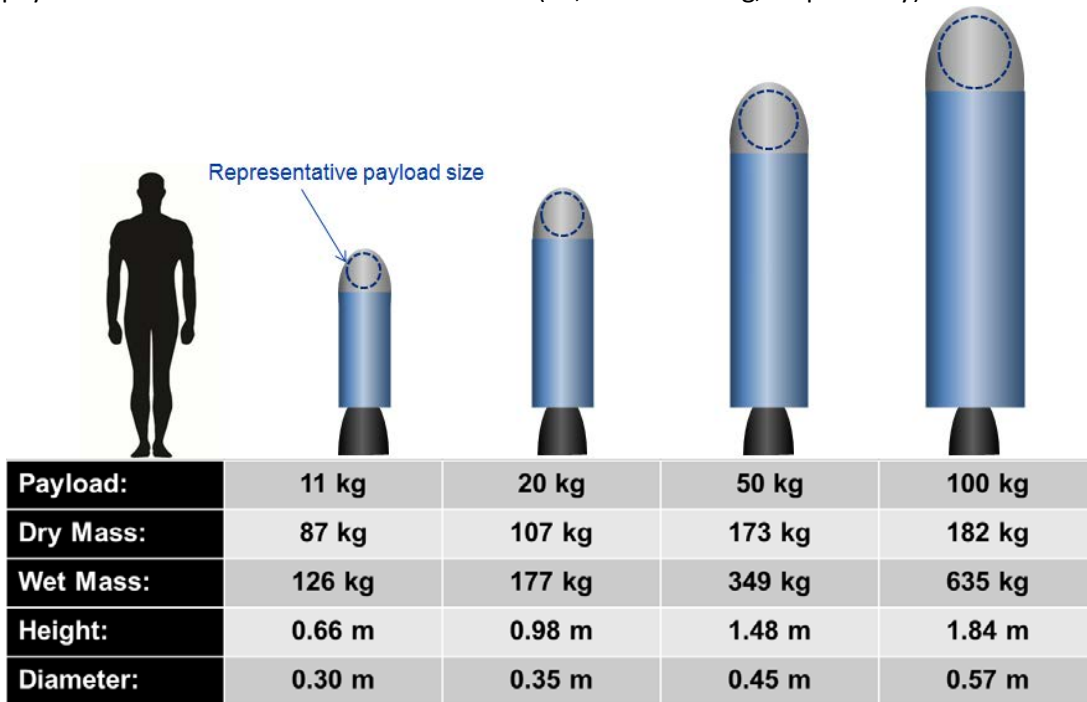
**Fig. S.1.** The mass capability for different sample container internal diameters assuming the lithology sample proportions from Table S.1. The minimum and maximum mass capabilities were calculated using the upper and lower bound of the estimated densities of each lithology (see text).



**Fig. S.2.** The maximum payload (kg) as a function of the ascent vehicle tanksize volume ( $m^3$ ).



**Fig. S.3.** Dimensions of the ascent vehicle as a function of payload size (sample mass) assuming an Aestus II engine with Monomethylhydrazine (MMH) propellant. The left-most vehicle represents the size of the vehicle required for the 11 kg payload, and the others explore what would be required to deliver larger payloads from the lunar surface to the eDSH (20, 50 and 100 kg, respectively).



**Fig. S.4.** Qualitative assessment of crater degradation state of craters along the short and long traverse (modified from Wilhelms, 1984)

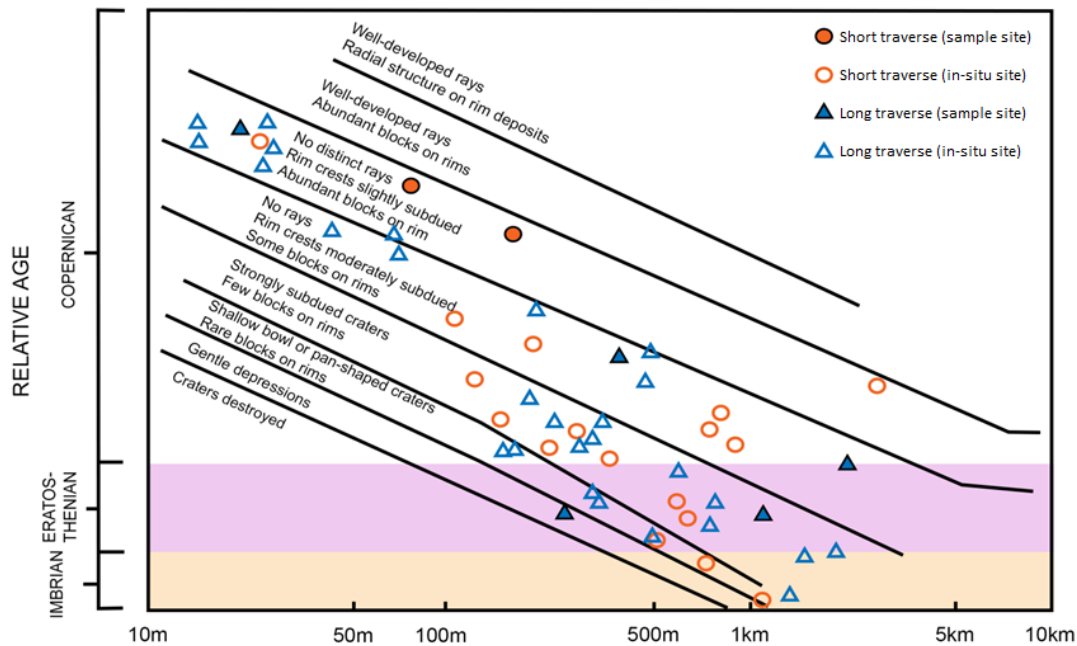


Figure 1A-B

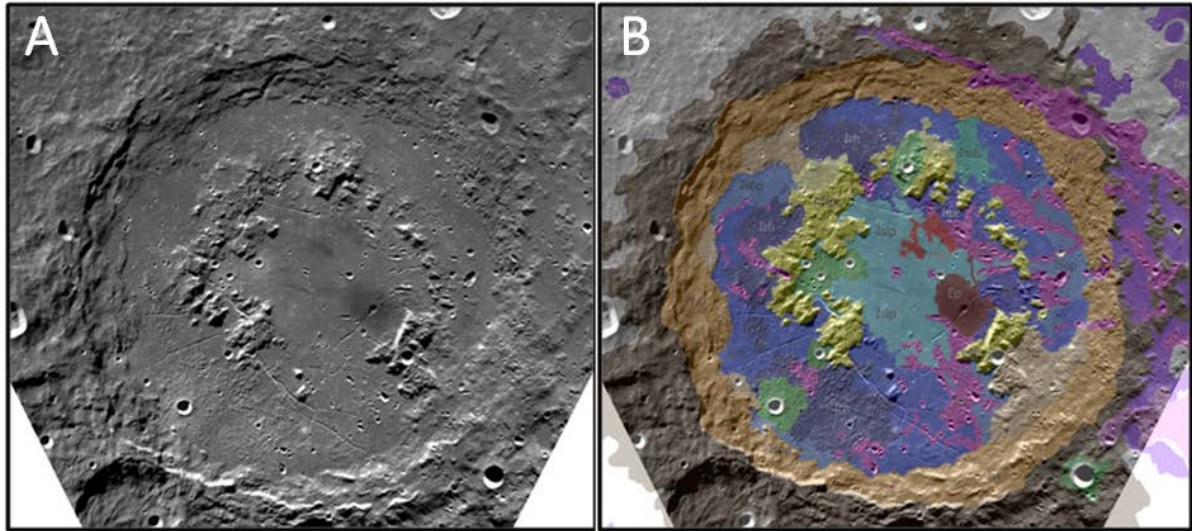


Figure 2

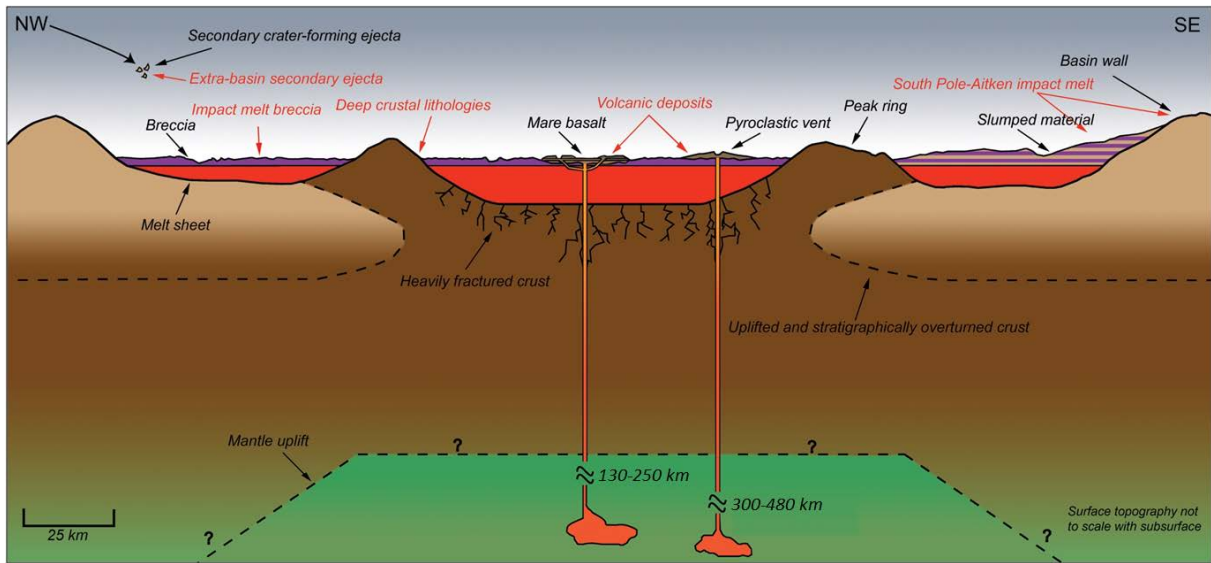


Figure 3

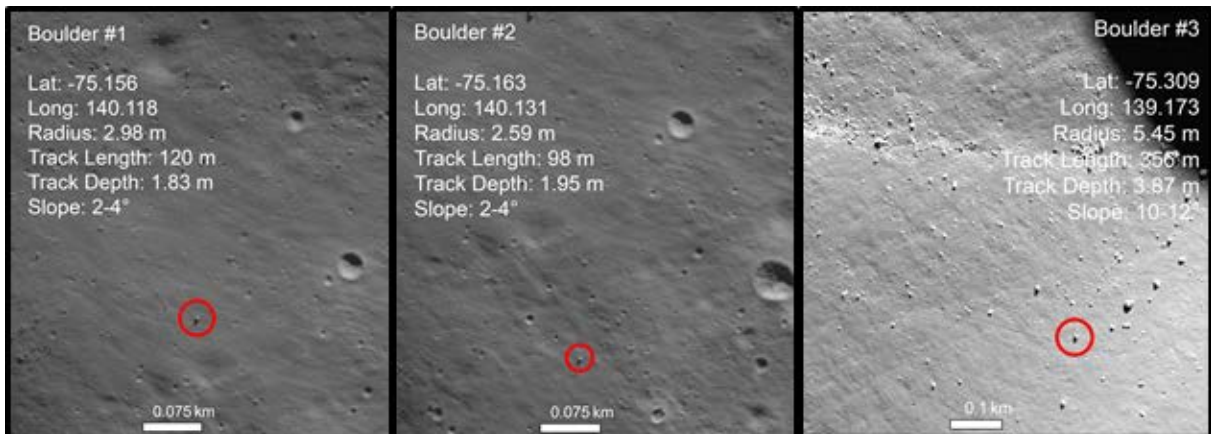
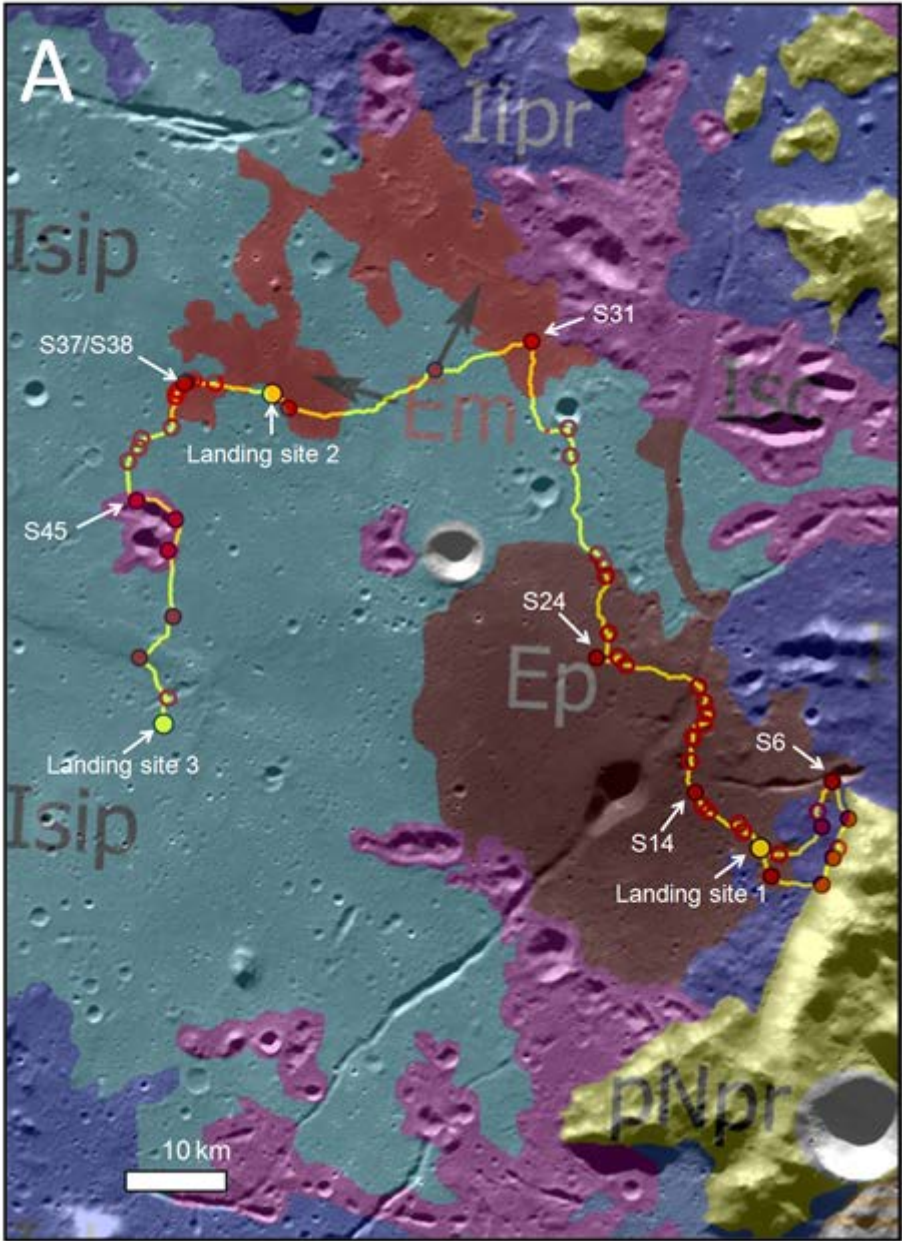


Figure 4A-B



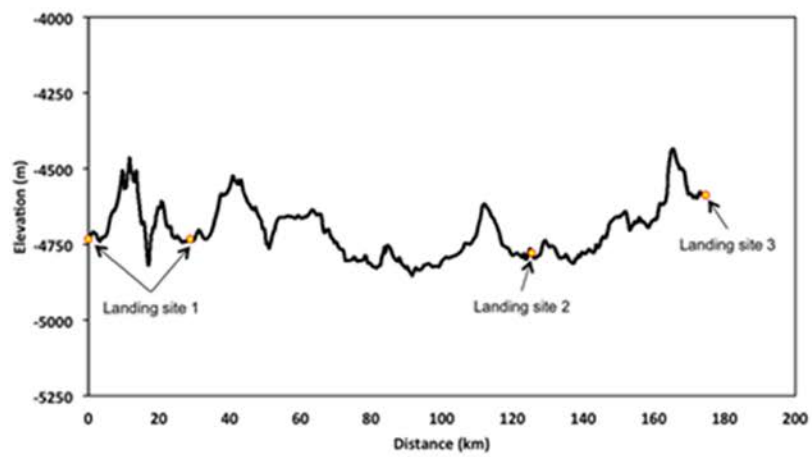
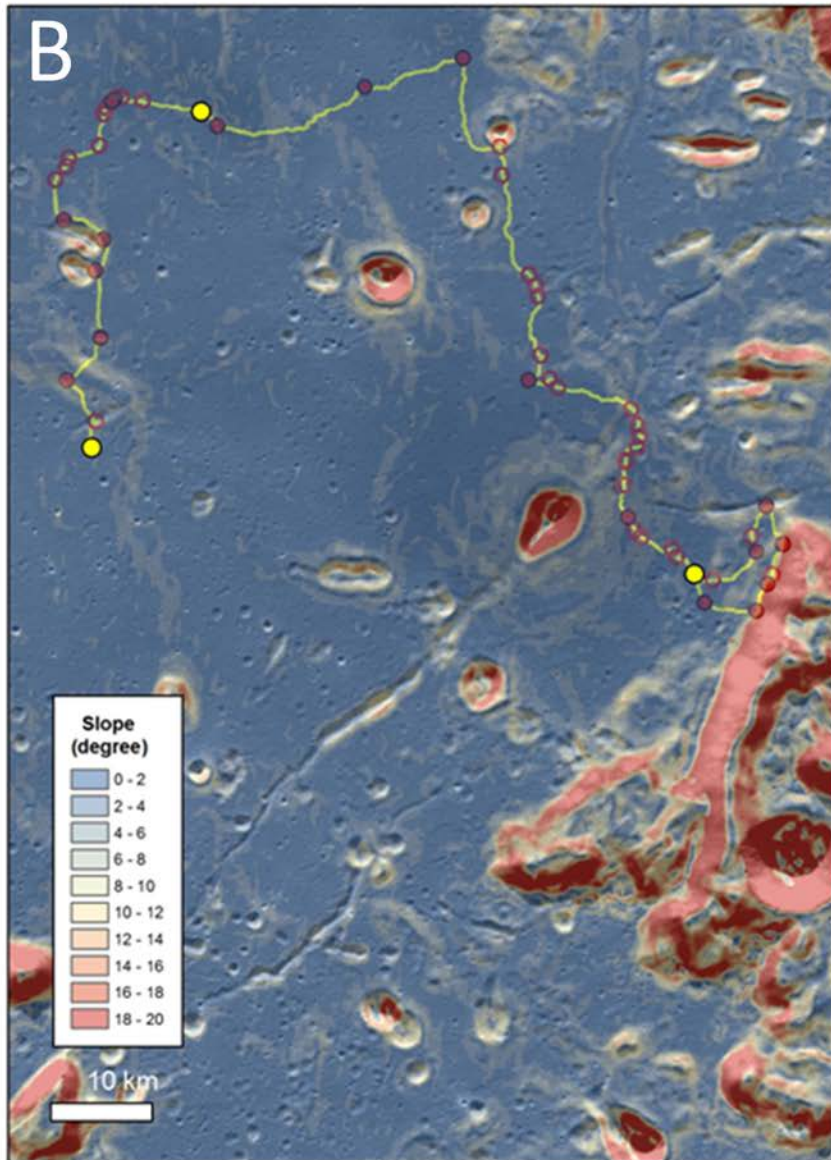


Figure 5A-E

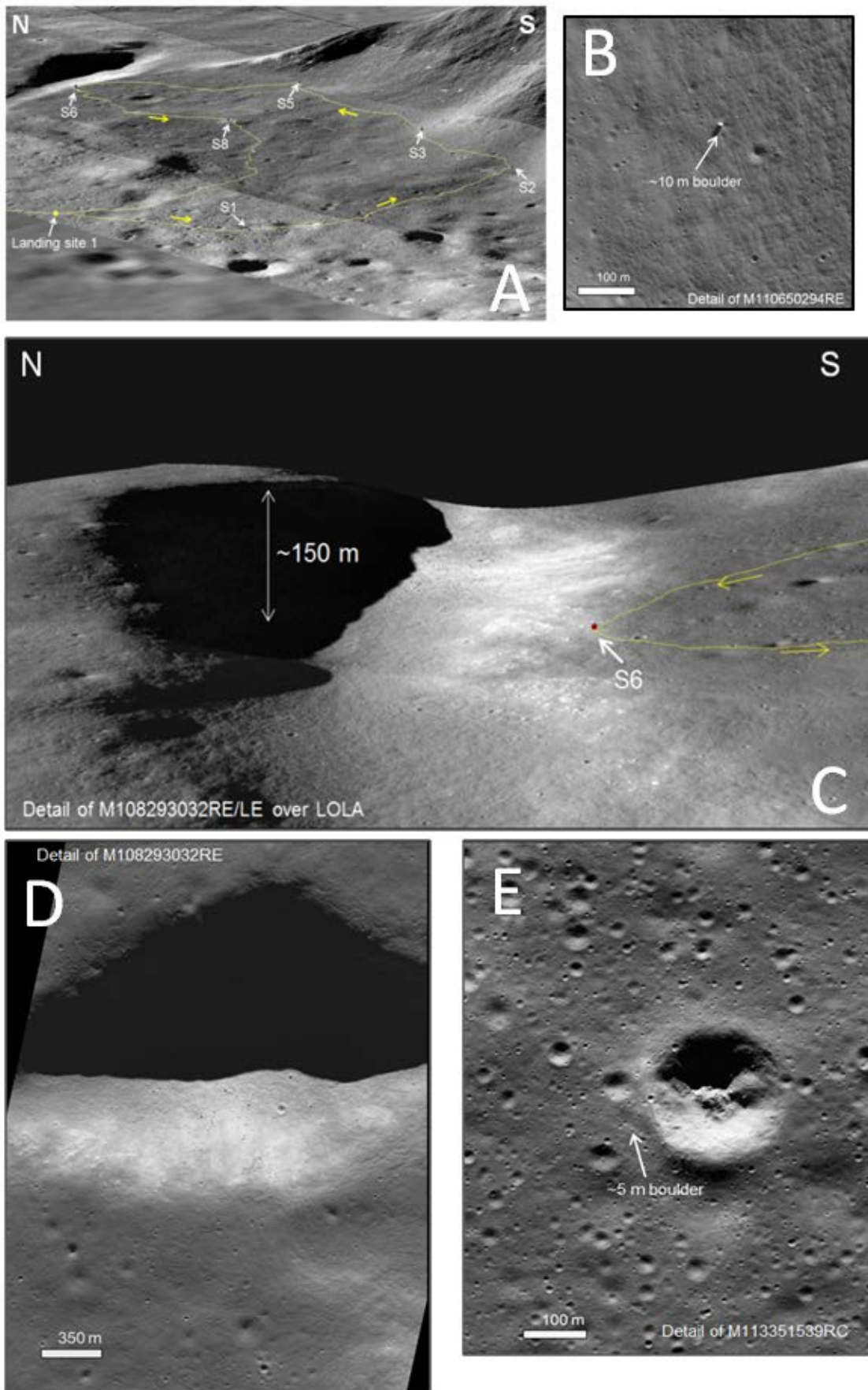


Figure 6

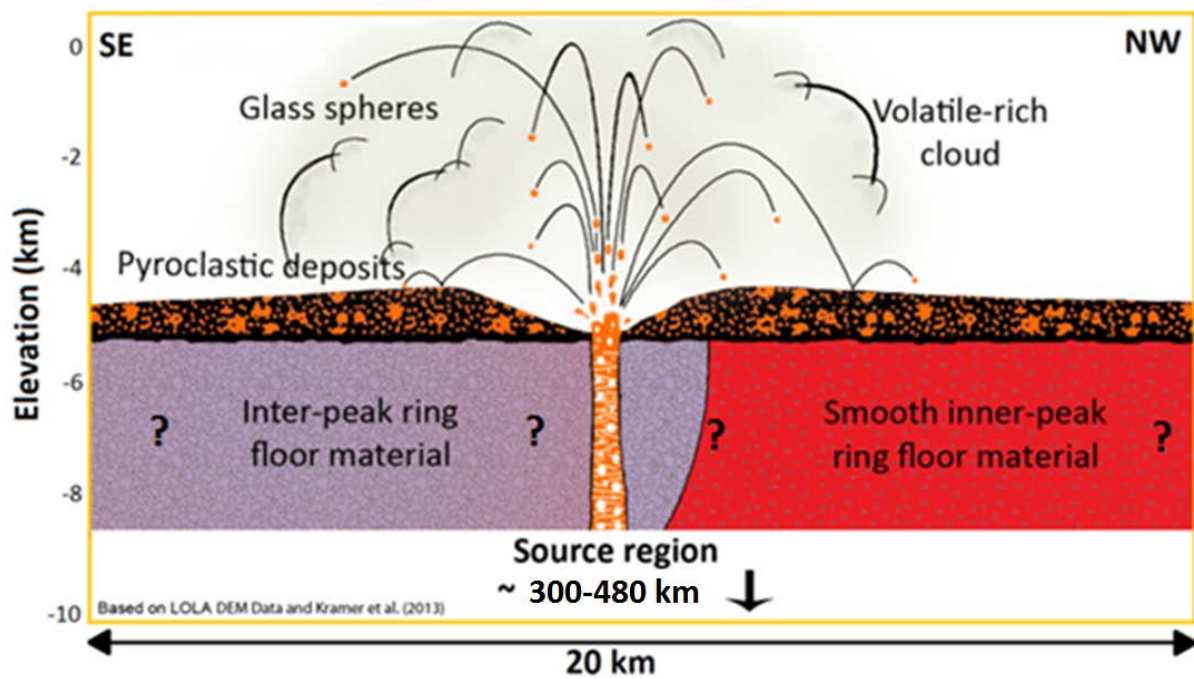


Figure 7

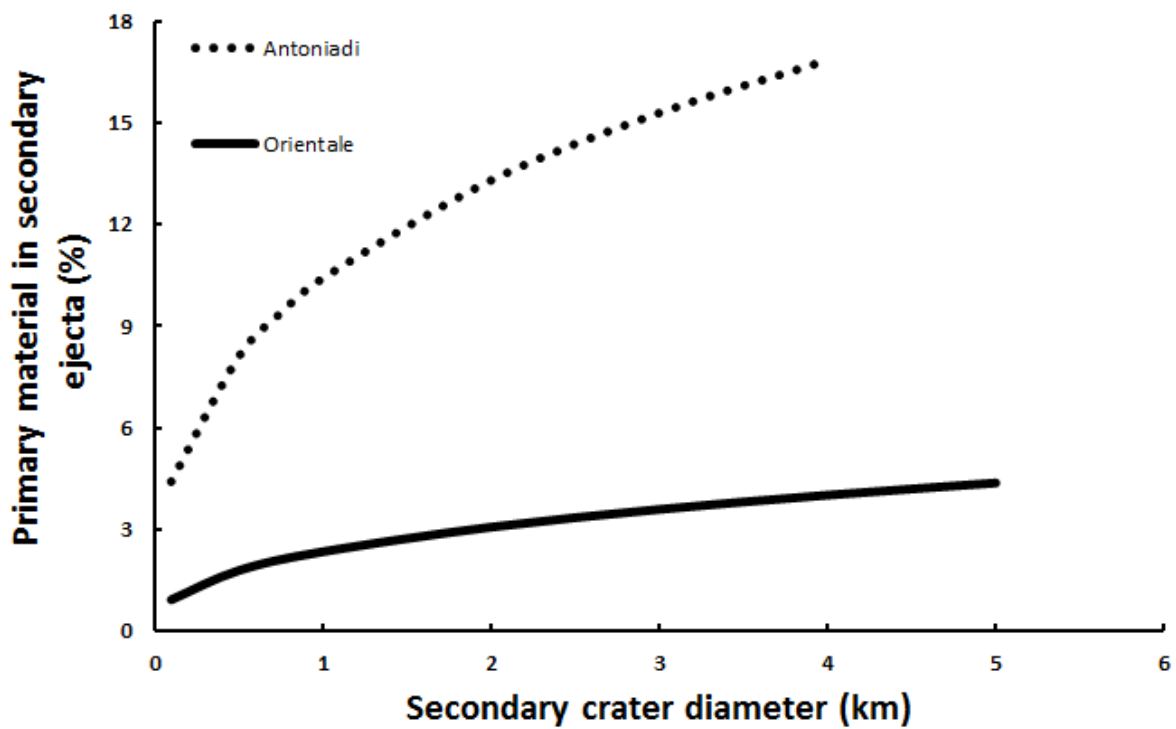
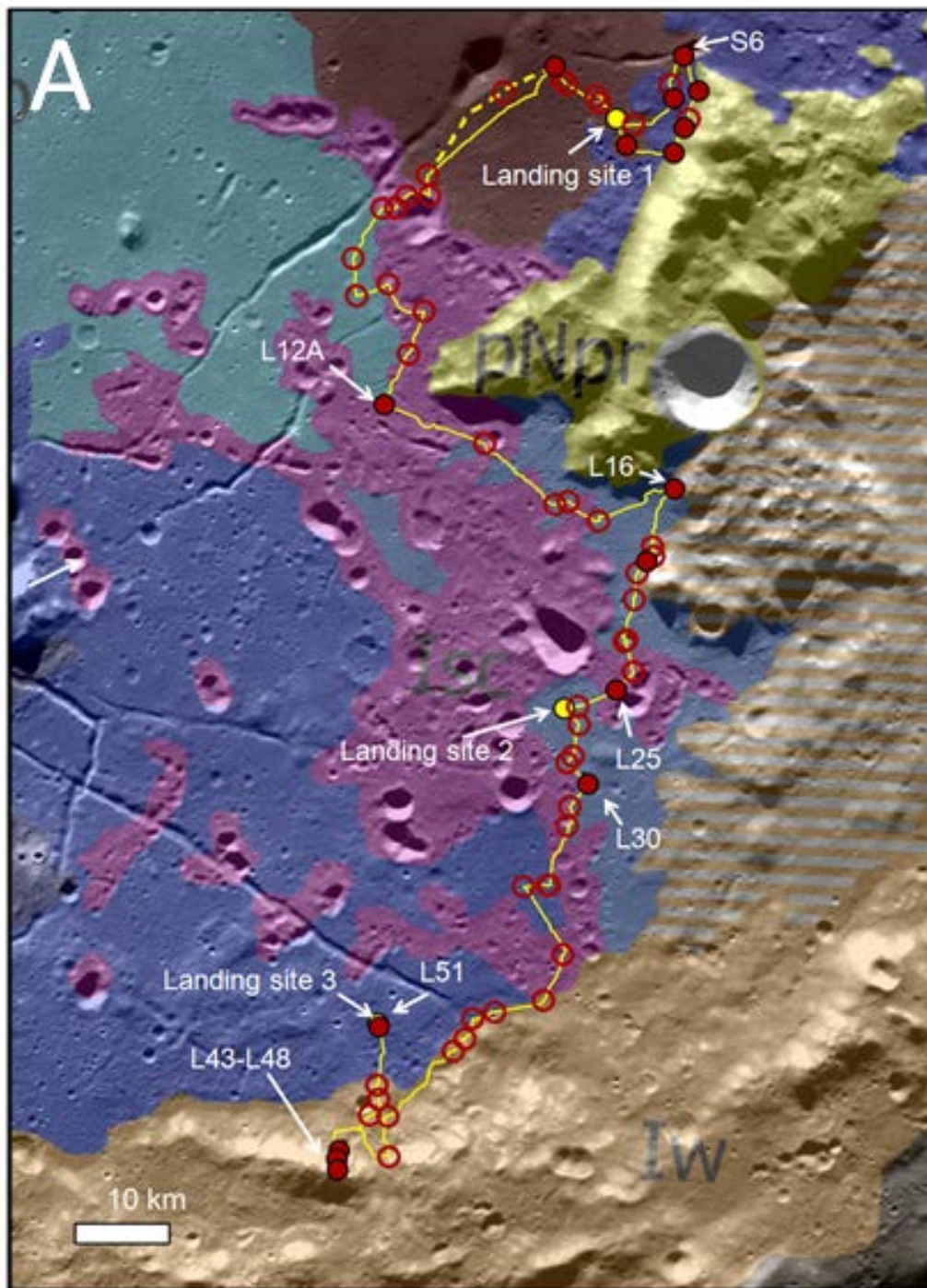




Figure 8A-B



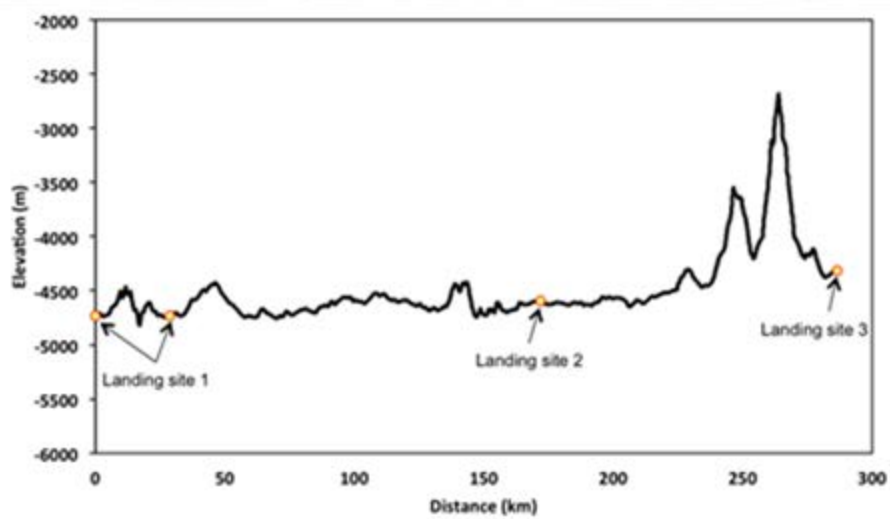
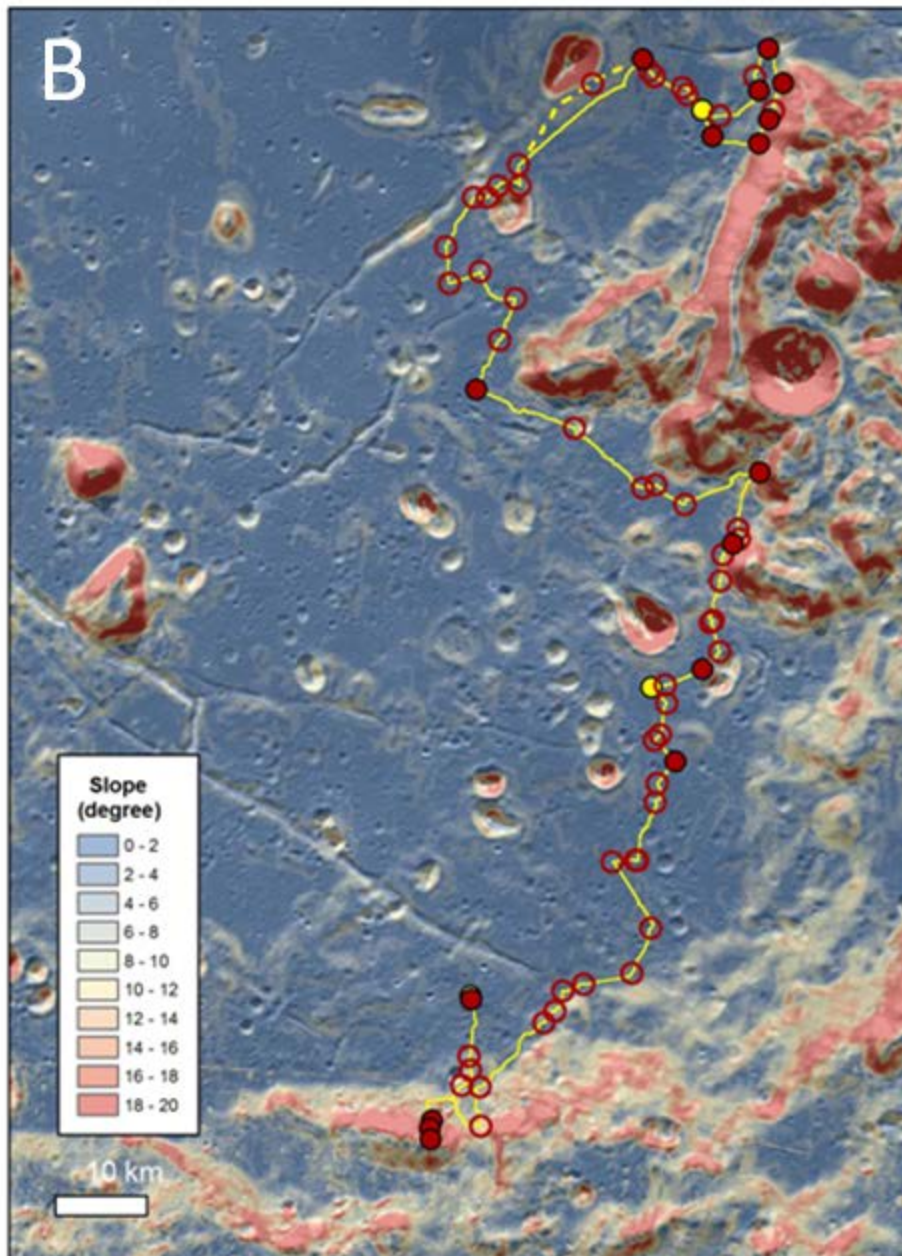
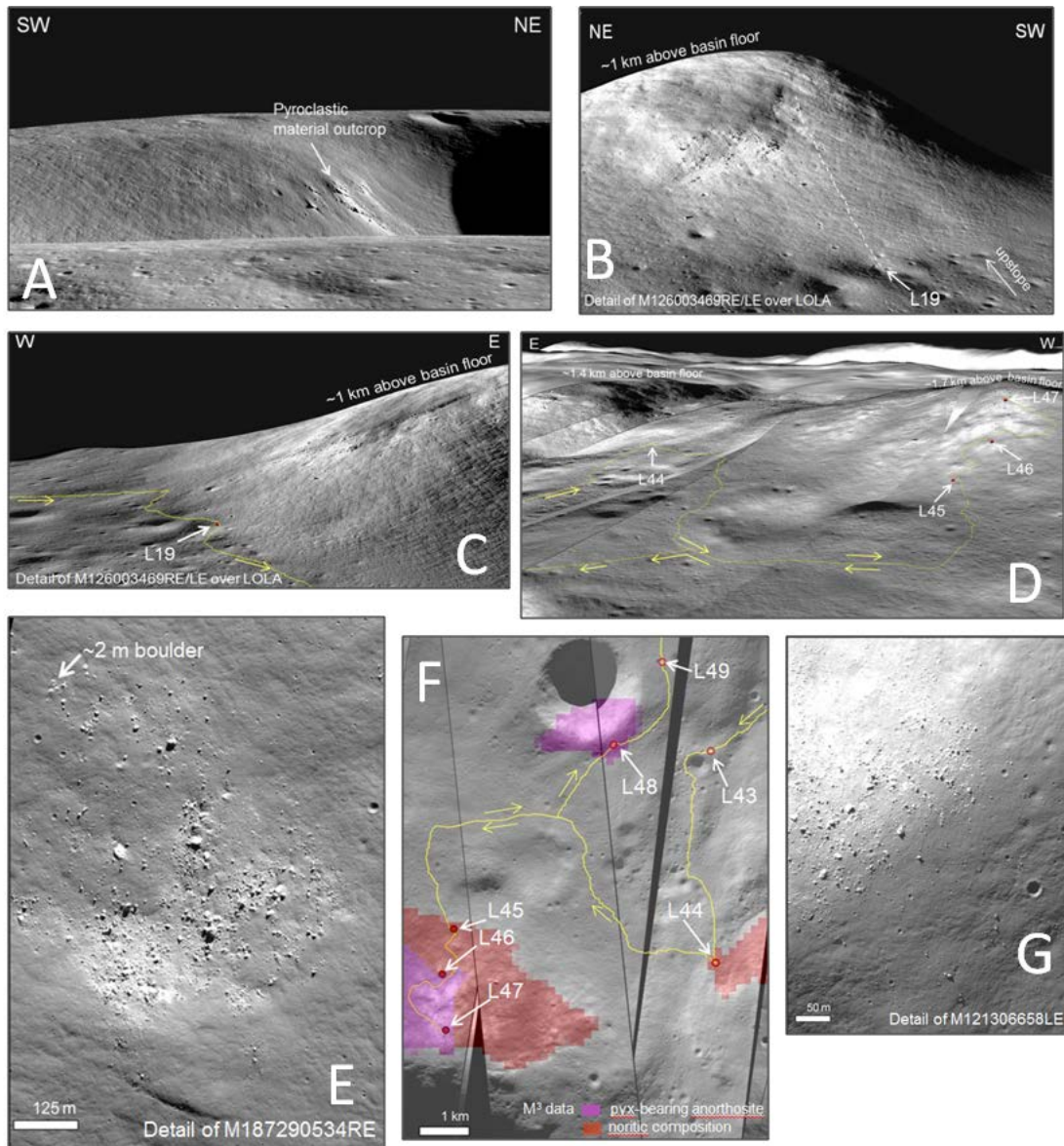


Figure 9A-G



**Table 1** Notional instrumentation suite assumed for ConOps assessment.

| Instrument  | Dimensions (cm)                           | Weight (kg) <sup>a</sup> | Power (W) <sup>a</sup> | Data rate (kbps)  |
|---|---|--------------------------|------------------------|-------------------|
| Ground penetrating radar<br>(ExoMars WISDOM) <sup>[1]</sup>           | Sensor: 10x10x1<br>Electronics:<br>10x6x6 | <3.50                    | <7.8                   | 44.5              |
| Arm-mounted Alpha<br>Particle X-Ray spectrometer (MER) <sup>[2]</sup> | 10.5x6x9                                  | <2.20                    | <7.3                   | 18.0**            |
| Gamma Ray spectrometer (JH APL) <sup>[3]</sup>                        | Sensor: 8x8x8<br>DPU: 10x15x5             | <1.82                    | <3.25                  | 0.01-0.1          |
| Neutron spectrometer<br>(Lunar Prospector/HYDRA) <sup>[1]</sup>       | 18x12x6                                   | <0.65                    | <1.8                   | 0.5               |
| Microscope camera (MER) <sup>[2]</sup>                                | 8x8x10                                    | <0.4                     | <0.4                   | 8000 <sup>b</sup> |
| Surface imaging camera<br>(MSL MastCam) <sup>[1]</sup>                | 11x29x12                                  | <1.0                     | <11.0                  | 1.26              |

<sup>a</sup>With 30% contingency<sup>b</sup>Defined as science data rate prior to on-board processing

References: [1] Shearer et al. (2010) [2] Arvidson and May (2010) [3] Wieczorek et al. (2015)

**Table 2** ConOps used for traverse times assuming the notional instrumental payload from Table 1.

| Station Activities   | Time (Earth hours) <sup>a</sup>               |
|--|---|
| Panoramic image using 3D imager (HD video<br>feed at other times) <sup>[1]</sup> | 8   |
| Position rover for in-situ target <sup>[1]</sup>                                 | 0.5   |
| GPR analysis <sup>[2]</sup>  | On while traversing                           |
| Neutron sensor analysis <sup>[2]</sup>   | On as when needed including during traversing |
| Position arm-mounted APXS <sup>[1]</sup>   | 0.5   |
| APXS analysis <sup>[4]</sup>   | 3.0   |
| Position GRS <sup>[1]</sup>  | 0.5   |
| GRS analysis <sup>[3]</sup>  | 1.0   |
| Position microscope camera (LRAC) <sup>[1]</sup>                                 | 0.5   |
| Microscope camera (LRAC) <sup>[4]</sup>  | 1.0   |
| Surface imager (MSL MastCam) <sup>[2]</sup>                                      | 0.5   |
| Sample collection <sup>[1]b</sup>  | 3.0   |
| Sample transfer to bag and storage <sup>[1]</sup>                                | 1.0   |

<sup>a</sup>Assuming one analysis per type of in-situ analysis<sup>b</sup>Sample collection may vary considerably dependent on collection method (e.g., scoop, rake, drilling)

References: [1] Potts et al. (2015) [2] Shearer et al. (2010) [3] Wieczorek et al. (2015) [4] Arvidson and May (2010) [5] Malin et al. (2005)

**Table 3** Summary of the NRC (2007) science goals that can be addressed within the short (a) and long traverse (b). Goals that with reasonable certainty can be addressed within the traverse are indicated in dark grey, goals that may be addressed are indicated in light grey and the top 10 of the highest science priorities are in italic and bold.

a

|   | a   | b   | c   | D  | e  |
|---|---|---|---|--|--|
| <b>1: Bombardment history of the inner solar system</b>   | <i>Test cataclysm hypothesis</i>                          | <i>Early Earth-Moon impact flux and age of SPA basin</i>    | <i>Establish absolute chronology</i>                      | Recent impact flux                                       | Role of secondary craters on crater counts   |
| <b>2: Structure and composition of the lunar interior</b> | <i>Thickness and lateral variability of lunar crust</i>   | <i>Chemical and physical stratification of lunar mantle</i> | <i>Size, composition and physical state of lunar core</i> | Thermal state and evolution of lunar interior            |  |
| <b>3: Diversity of lunar crustal rocks</b>                | <i>Extent and composition of differentiation products</i> | <i>Age, distribution and origin of lunar rock types</i>     | Composition of lower crust and bulk Moon                  | Local and regional complexity of lunar crust             | Extent and structure of megaregolith         |
| <b>4: Lunar poles and volatiles</b>                       | <i>Compositional state and distribution of volatiles</i>  | Source(s) for lunar polar volatiles                         | Dynamical processes of polar volatiles                    | Physical properties of cold polar regolith               | Polar regolith and ancient solar environment |
| <b>5: Lunar volcanism</b>                                 | Origin and variability of basalts                         | Age of youngest and oldest mare basalts                     | Compositional range and extent of pyroclastics            | Flux and evolution of lunar volcanism                    |  |
| <b>6: Impact processes</b>                                | Existence and extent of melt sheet differentiation        | Structure of multi-ring impact basins                       | Physical aspects of crater formation                      | Lateral and vertical mixing of ejecta and local material |  |
| <b>7: Regolith processes</b>                              | Characterizing ancient regolith                           | Physical properties of regolith                             | Regolith modification processes                           | Studying rare materials in regolith                      |  |

**b**

|   | <b>a</b>  | <b>b</b>  | <b>c</b>  | <b>d</b>   | <b>e</b>                                     |
|---|---|---|---|--|--|
| <b>1: Bombardment history of the inner solar system</b>   | <i>Test cataclysm hypothesis</i>                          | <i>Early Earth-Moon impact flux and age of SPA basin</i>    | <i>Establish absolute chronology</i>                      | Recent impact flux                                       | Role of secondary craters on crater counts   |
| <b>2: Structure and composition of the lunar interior</b> | <i>Thickness and lateral variability of lunar crust</i>   | <i>Chemical and physical stratification of lunar mantle</i> | <i>Size, composition and physical state of lunar core</i> | Thermal state and evolution of lunar interior            |  |
| <b>3: Diversity of lunar crustal rocks</b>                | <i>Extent and composition of differentiation products</i> | <i>Age, distribution and origin of lunar rock types</i>     | Composition of lower crust and bulk Moon                  | Local and regional complexity of lunar crust             | Extent and structure of megaregolith         |
| <b>4: Lunar poles and volatiles</b>                       | <i>Compositional state and distribution of volatiles</i>  | Source(s) for lunar polar volatiles                         | Dynamical processes of polar volatiles                    | Physical properties of cold polar regolith               | Polar regolith and ancient solar environment |
| <b>5: Lunar volcanism</b>                                 | Origin and variability of basalts                         | Age of youngest and oldest mare basalts                     | Compositional range and extent of pyroclastics            | Flux and evolution of lunar volcanism                    |  |
| <b>6: Impact processes</b>                                | Existence and extent of melt sheet differentiation        | Structure of multi-ring impact basins                       | Physical aspects of crater formation                      | Lateral and vertical mixing of ejecta and local material |  |
| <b>7: Regolith processes</b>                              | Characterizing ancient regolith                           | Physical properties of regolith                             | Regolith modification processes                           | Studying rare materials in regolith                      |  |

