HABITABILITY POTENTIAL OF LUNAR PIT CRATERS: MARIUS HILLS, MARE TRANQUILITATIS, LACUS MORTIS AND MARE INGENII PIT.
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Introduction: Subsidence or collapse craters, also called pit craters, can be found on the Moon and throughout the Solar System, including our planet. These depressions in the terrain are not formed by impacts but rather by the collapse of the terrain over a void, usually creating circular-shaped hollows. Similar to how lava tubes-pits are formed on the Earth, on the Moon, these features could be the entrance to underground caves formed when lava tube ceilings are not resistant enough to support their weight and collapse [1, 2]. Some of them could even be interconnected if their origin is the same volcanic tube through which lava flowed in the past. Consequently, planetary pit craters and potential subsurface caves are promising astrobiological regions due to their properties to preserve their own microclimate [3]. They also offer a natural shield against radiation (below or at 6 meters depth) [4] and harsh surface conditions. Surface exposed water ice was found in the lunar polar regions [5] and in simple craters [6], so lunar pit craters could preserve water ice reservoirs inside or near them. Caves have been described as possible first human settlements on the Moon and Mars, offering a permanent and safe refuge for astronauts and equipment storage [7]. On top of that, the protection that is providing this natural shelter offers an additional interest: an intact lava tube in pristine conditions proper to understand the geological history of the Moon.

The aim of this study is to define a global list of the best pit craters suitable for establishing a lunar exploration base, so that future missions to the Moon can benefit from this information.

Methodology: We analyzed the catalogue of 278 lunar pit craters using the planetary data system (PDS) to detail their possible habitability, prioritizing those related to potential lava tube candidates found on the Moon [8, 9]. To select the best candidates, we have considered the following points of view: (1) morphological characteristics; (2) the proximity of each other's and its possible internal connections; (3) associations with various geological structures (such as lobate scarps, wrinkle ridges, maria or impact craters); (4) their possible origin; (5) different type of geological materials and their proximity to areas abundant in resources (water ice, REE or other materials); (6) their proximity to areas more suitable for landing on the Moon; and (7) proximity to current and future human and robotic missions.

We also mapped and located the best candidates by overlaying current pit crater locations from the LROC atlas to different global and regional lunar datasets, such as the global geologic map of the Moon (USGS, [10]), in order to obtain information on the different regions on the Moon and their properties (material type and age); the Kaguya (SELENE) mission maps (covering latitudes from -60° to 60°); and the North and South pole LOLA-LRO lunar maps, that provide the information on the elevation profile. A volcano-tectonic feature layer is also added to find some clues about how the pit craters in an area might be connected and how large the subsurface caves would be.

Results and discussion: After applying our selection criteria and scoring each of the pits registered in the atlas, we studied in detail the best candidates: Marius Hills Pit (MHP), Mare Tranquilitatis Pit (MTP), Mare Ingenii Pit (MIP) and Lacus Mortis Pit (LMP).

MHP is the most ideal candidate for a lunar base, as it meets all our criteria: according to the data from GRAIL and the swirls maps the two pits located at this region seem to be connected by a sublunarean lava tube that comes from the southwest and coincides with a magnetic anomaly (being able to be the source of the magnetism a buried horizontal half cylinder) [11]. This presumed lava tube would point towards Marius Hills, where this pit is located, a volcanic region of the Oceanum Procellarum, rich in Fe and Ti [12], which would imply bigger lava tubes. The final and strongest evidence of MHP being a skylight [13] is its connection to the volcanic channels, as it is located just on top of one. It has a ceiling width of 21 meters and a depth of 40 meters. Its inner space extends beyond 12 meters below the ceiling.

MTP is the second most preferred candidate for exploration. This candidate is not located on top of a volcanic channel, as MHP, but it is located in a terrain rich in Fe and Ti, and near a collapsed lava tube aligned with a less-gravity GRAIL zone. In principle, although this pit is not coincident with any volcanic channel or rille observed on the surface, so if any sublunarean lava tube exists, it could be invisible to the cameras. There is no swirl evidence, but MTP is located in a magnetic anomaly. A particularity of MTP is that this pit is one of the two only lunar pits that has presented a thermal signature measured thanks to the Diviner instrument data from LRO [14]. Even though this is not evidence to prove the connection with a sublunarean lava tube, this pit is still the second most preferred candidate because it is the one that has the biggest inner space, with a sublunarean soil extending up to 20 meters below the ceiling. Its ceiling width is 47 meters.

MIP is the third candidate in our ranking. Located in the Mare Ingenii (far side), in a less-gravity zone according to GRAIL data, and totally isolated from other pit craters, having the nearest one at 250 km. This pit is located on a swirl and has the second strongest magnetic anomaly of the list, at 78 nT, just after MHP. Looking at the images of LROC-ASU, there is an overhang of 10-20 meters of inner space and the ceiling thickness is approximately 50 meters [15]. Recently, thanks to the Diviner instrument data from LRO, a thermal signature has been detected at the interior of the pit [14], just like MTP. We must mention that this is not enough to discard all the other candidates because the instruments do have not enough sensitivity to detect temperature changes induced by the presence of lava tubes (0.1 K) [14].

LMP is the last-best candidate following our ranking because it has no confirmation of correlation of a sublunarean void space, such as the other candidates. It is located in a very poor Fe and Ti zone, but it is still in our ranking because it is the only one in the list that has a ramp-shaped inner slide to become easily accessible to the inside with a slope of 22° [16]. The surface opening of this feature corresponds with the second biggest mare pit, and it is located within a less-gravity zone measured by GRAILs, just between Lacus Mortis Pit and Highland 1. Precisely, this region is hosting the rime Bürg, a 60 km long rime, which is not considered a volcanic channel but could be connected to two extinct volcanoes. This evidence of past volcanism, added to the found pyroclastic deposits around the graben, could indicate that there was volcanic activity in the past, so the existence of a sublunarean lava tube coincident with the rime Bürg cannot be disregarded.

Conclusions: After categorizing the 273 pit craters, we studied in detail the four most viable candidates on the lunar surface. Using the data from GRAILs, Kaguya, Lunar Prospector and Lunar Reconnaissance Orbiter, amongst already conducted studies of these pits, we determine that the most suitable candidate could be Marius Hills Pit, as it is fulfilling all our requirements, followed by Mare Tranquilitatis and Ingenii Pits and finally Lacus Mortis Pit (that could be a potential candidate to visit to study more about its morphology due to its easy access). We still know little about the pit craters and the presumed ancient lava tubes that they would give access to. More in-situ missions and pit crater-targeted observations will provide us with a better understanding of the full potential of these pits. Future work encompasses a further investigation using the data from the Lunar Radar Sounder of Kaguya to ensure there are sublunarean voids related to the proposed lunar skylights.

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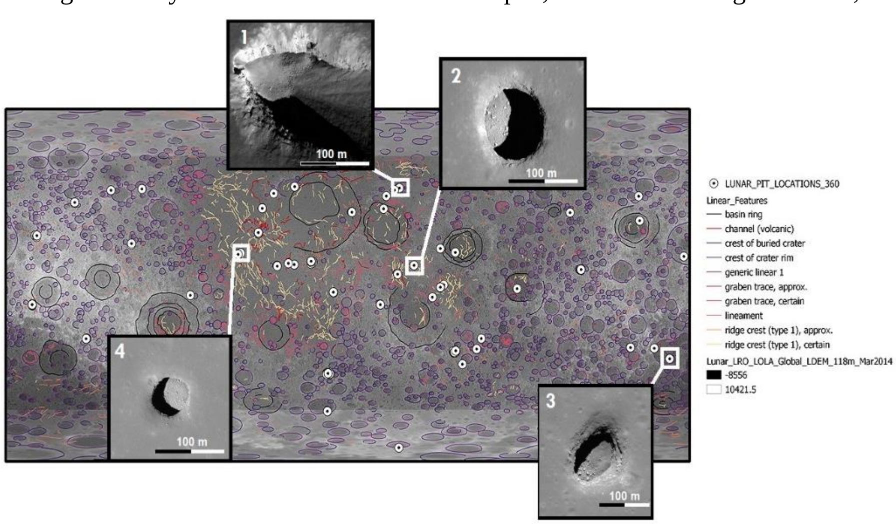

Figure 1. Atlas of pit lunar craters [9], over the LOLA-LRO (NASA) elevation model, including some geologic structures (basin rings, volcanic channels, ridges, grabens, lineaments, ridges) and the selection of our last four best candidates for future exploration and habitability: (1). Lacus Mortis Pit (LMP); (2). Mare Tranquilitatis Pit (MTP); (3). Mare Ingenii Pit (MIP); and (4). Marius Hills Pit (MHP).