Detection and classification of potential caves on the flank of Elysium Mons, Mars

Ravi Sharma\textsuperscript{1} and Neeraj Srivastava\textsuperscript{2}

\textsuperscript{1} J.J.T. University, Jhunjhunu, Rajasthan 333001, India; science.rs08@gmail.com
\textsuperscript{2} Planetary Science Division, Physical Research Laboratory, Ahmedabad 380009, India

Received 2022 February 19; accepted 2022 April 7

Abstract The Martian caves have revived interest in the field of subsurface exploration because they are the potential destinations for future human habitats and astrobiological research. There are many pits on Mars, but some of them look like collapsed cave roofs. These special pits are formed by the collapse of the surface materials into the subsurface voids space. The signature of life is probable in a subsurface cave on Mars as the subsurface environment can protect life from the harsh and dangerous radiation environment of the surface. In a cave, there may be an abundance of minerals, fluids, and other key resources. Therefore, locating the access point of the subsurface cave is essential and crucial for formulating plans for robotics/human explorations of the Red Planet, Mars. We have used remote sensing data from MRO (Mars Reconnaissance Orbiter; NASA), MGS (Mars Global Surveyor; NASA), and Mars Odyssey (NASA) for identifying, mapping, and classifying selected special pit candidates on the flank of Elysium Mons, Mars. A total of thirty-two special pit candidates have been identified and classified based upon morphology and geological context. Out of these, twenty-six are newly discovered ones. The thermal behavior of twenty-three special pit candidates confirms that the special pits are radiating heat energy at nighttime, similar to potential caves. Also, cave entrances have been detected in nine candidates using the data from HiRISE camera onboard MRO. These sites could be important destinations for future robotics/human exploration and the search for life on Mars.

Key words: planets and satellites: individual (Mars) — planets and satellites: surfaces — planets and satellites: general

1 INTRODUCTION

There are many pits on Mars, but some of them look like collapsed cave roofs. Such a pit is an opening on the cave roof or ceiling to admit the natural light. These pits are referred to as special pits in this study, and they form by the collapse of surface material into the subsurface void spaces. They can be associated with tube-fed lava flows, volcanic-tectonic features, or rille structures \citep{Cushing2012, CushingEtAl2013}. The sunlight enters the cave entrance zone from the access point of the pit, and very high-temperature fluctuation occurs in the portion that is directly illuminated. The surrounding areas in the twilight zone exhibit only minor temperature changes because they are illuminated only by scattered light.
Most importantly, the temperature in the un-illuminated part of the cave remains more—or—less constant. Therefore, there is the possibility of an abundance of ice and other cave resources in this zone (Boston et al. 2003a; Hill & Fort 1997; Romero 2009; Bairagya 2014). The caves also protect from dust storms, high ultraviolet radiations, and cosmic rays (Boston et al. 2004). Thus, the caves are the potential sites for future robotics/human explorations of the surface of Mars (Boston et al. 2003b). Considering these aspects in this study, we have explored special pit candidates in the Elysium Mons region of Mars with the help of existing datasets from various remote sensing missions. There are three proposed human exploration zones around Elysium Mons. These are Hebrus Valles (Davila et al. 2015), Phlegra Dorsa (Barker et al. 2015), and Cerberus Fossae (Wright et al. 2015). Therefore, future human/rover-based exploration into the potential caves on Elysium Mons is possible to discover the critical resources.

Special pits were discovered on Mars in the year 2007 in the Tharsis region (Cushing et al. 2007). Cushing (2021) has released an updated version of the Mars Cave Candidate Catalog, which includes forty-four special pit candidates present on the flank of the Elysium Mons. Out of these, we have included six candidates in this study for detailed morphometry and thermal examination. In addition, we have searched and characterized new special pits in the Elysium Mons region of Mars in this study using remote sensing datasets from Mars Reconnaissance Orbiter (MRO), Mars Global Surveyor (MGS), and Mars Odyssey missions of NASA.

2 DATASETS USED

In this study, we have used imaging datasets, spectrometer data, and altimetry data from several remote sensing missions to Mars by NASA. These include panchromatic data from High-Resolution Imaging Science Experiment (HiRISE) and ConText (CTX) camera from Mars Reconnaissance Orbiter (MRO; 2005–present) (Malin et al. 2007), and THEMIS Infrared Projected Brightness Temperature Image (IRPBT) data from Mars Odyssey (NASA) (Christensen et al. 2004, 2017). We have also used Mars Orbiter Laser Altimeter (MOLA) data from Mars Global Surveyor (NASA) (Smith et al. 2001, 2003). The spatial resolutions for these datasets are ∼0.25 m/pixel for HiRISE, ∼5–6 m/pixel for CTX, ∼100 m/pixel for THEMIS IRPBT, and ∼463 m/pixel for MOLA Mission Experiment Gridded Data Records (MEGDRs). The THEMIS IRPBT data is computed from Band 9 (12.57 µm) calibrated spectral radiance values assuming atmospheric opacity of 0.0 and surface emissivity of 1.0 (Christensen et al. 2017). Apart from this, we have used geological unit layers from Tanaka et al. (2014), and Mars Cave Catalog from Cushing & Okubo (2015), and Mars Cave Catalog from Cushing (2015, 2019).

3 METHODOLOGY

3.1 Identification of special pit candidates

Initially, CTX and/or HiRISE images have been used to detect special pits based upon morphological investigations. As viewed from the orbit, the special pits occur as a mostly circular structure having a collapsed cave roof and exhibiting a shadowed appearance in the un-illuminated part (Cushing et al. 2013). Unlike any impact craters, they are devoid of elevated rims, ejecta blanket, and rays (Fig. 1). Further, the special pits show a warmer appearance than the surrounding area at night time (Cushing et al. 2015; Jung et al. 2014; Sharma et al. 2019; Sharma & Srivastava 2021) because the heat from the outer surface is easily radiated while the loss of heat stored inside a cave is greatly inhibited and the cave radiates most of the heat energy through the special pits in the night time (Antoine et al. 2009, 2011; Lopez et al. 2012), therefore special pits are considered as potential caves. We have used the night time THEMIS IR data of the northern summer season (Solar Longitude;
Potential caves on the flank of Elysium Mons, Mars

Ls 90–180) for thermal observations. During the northern solar summer, the solar insolation is high, resulting in higher surface temperatures. Surface heat is a source of heat transferred to a subsurface cave. A greater amount of heat reaches the subsurface in the northern solar summer therefore the possibility of excess amount of heat coming out from the special pit is also high. Therefore, it is appropriate to use the northern summer season data of the THEMIS IR observations. Here, "THEMIS IR" refers to the THEMIS Band–9 data (centered at 12.57 µm). Band–9 is useful because it detects surface brightness temperatures at a high signal–to–noise ratio (SNR) even at low temperatures. Primarily, the heat exchange between the subsurface caves and the outer surface occurs through the circulation of air (Cigna 1968). As per thermodynamics, heat flows from the direction of high temperature to low temperature (Boltzmann 1974). The temperature of the surface of Mars drops steadily at night (Coblentz 1925; Ferguson et al. 2006). At midnight time, the difference in the temperature of the special pit and the surrounding area is maximum therefore, it is appropriate to use the midnight data of the THEMIS IR observations.

We have restricted the extent of the surrounding area to a circular buffer zone of radius 500 m. The mid–nighttime temperature difference of the surrounding region (radius 500 m) of a special pit candidate TD has been calculated by estimating the difference between the candidate special pit point location night–time maximum temperature (Tmax) and their average surrounding (radius 500 m) temperature (Tmean). While estimating Tmean the temperature of the hotter pixel/pixels has not been included. In most of the cases, we have carried out thermal observations around midnight time from ~23:30 to 2:00. The thermal observation data of night time ~21:00 to 22:00 has been used in a few cases where midnight data was not available. The special pit shows a warmer appearance than the surrounding area, if TD > 0. Apart from these, the temperature of the potential cave floor fluctuates with much lower diurnal amplitudes than the nearby surfaces (Cushing et al. 2015). Therefore, we have calculated the diurnal amplitudes of the special pit candidate point location and the surrounding region. For this, Tmax, Tmean, and TD have been calculated for the thermal observations during the day (D) as well, around ~13:00–14:00. Here, it is important to mention that the temperature data of the daytime and the nighttime for different special pit candidates are not corresponding to the same day on Mars.

3.2 Classification of Special Pit Candidates

3.2.1 Morphology

These special pit candidates are classified into types of Atypical Pit Craters (APC) on the basis of morphology. According to Cushing et al. (2015), the APC I type candidates are bell–shaped and they possess overhanging walls and rims. The overhanging rim is thinner on the surface and thicker with increasing depth. If the overhang is symmetrical around the pit, the diameter of the cave floor may be approximately double that of the surface aperture. The APC II candidates show near–vertical walls for the upper part and overhanging walls in the lower part. The APC IIIs possess near–vertical walls with the absence of overhanging walls. Mostly, the APC I possess a flat cave floor, and the talus material is absent in it. The APC II has a bowl–shaped cave floor with the presence of talus material, and APC III has a flat cave floor with dust–covered rubble. Thus, the lateral extent of the overhanging walls decreases in APC II in comparison to APC I. It is to be noted that APC II may be misinterpreted as APC III in nadir observations unless the presence of overhangs at the base of pit walls is evident (Cushing et al. 2015).

We have estimated their true vertical depth at the point located at the edge of the shadow. The depth (D) of the special pit candidates have been estimated from the length of shadows (Ls), the solar incidence angle (i), and the emission angle (e) at the time of the observation,
using the approach of Cushing et al. (2015). Formulas, \( D = \frac{Ls}{\tan(i) - \tan(e)} \) and \( D = \frac{Ls \cos(i) \cos(e)}{\sin(i+e)} \) have been used to calculate the depth of the special pit candidates for Phase Angle \(<i\) and Phase Angle \(>i\), respectively. Here, the length of the visible shadow (\(Ls\)) is the horizontal distance in the direction of illumination from the shadow-casting point on the rim to the edge of the shadow cast upon the floor, and depth (\(D\)) is the true vertical depth at that point.

3.2.2 Geological Context

Besides the morphometric characterization of the special pits, we have also classified them based on their formation mechanism and geological context. The nature of the origin of the pits in this study should be mostly volcanic or tectonic since they are situated on the flank of Elysium Mons. During volcanism, there is a movement of magma in the subsurface and lava on the surface. Both these activities can result in the formation of pits due to different processes.

(i) Lava Tubes (LT) – Low-viscosity lava flows on the surface. The upper layer of the lava flow cools relatively faster. Therefore, the top layer hardens, which results in the formation of a tube. The rapid flow of lava through the tube decreases with time, and finally, the tube is left with no lava flow. The empty tube would have hard boundaries and space inside (Valierio et al. 2008). If the roof of this tube collapses, a special pit is formed, which provides access to the lava tube cave.

(ii) Horizontal Magma Conduit (HMC) – The horizontal propagation of magma through flank conduits form a horizontal magma conduit. The subsurface flow of magma forms the underground tubes (Neri 2010). The overhead material of this tube can fall due to tectonic activities, which results in the formation of a special pit that is connected to the subsurface tube. In this case, only the pit would be visible, and no tube would be observed on the surface.

(iii) Tectonic Feature (TF) – The region with a high influx of subsurface magma flow would have a large tectonic activity that results in the formation of rift zones. The strong tectonic activities in the rift zone can produce faults and grabens. In these cases, the pits are associated with visibly discernable tectonic features on the surface. On most occasions, these pits candidates form a chain (Cushing et al. 2015).

The special pit candidates have been classified as Lava Tube (LT) special pits when they are associated with lava tubes. Tectonic Feature (TF) special pits when they are associated with fractures, faults, or graben. If the special pit candidates are located on a volcanic flank but are not associated with either lava tube or tectonic features, they are classified as Horizontal Magma Conduit (HMC) special pits.

3.3 Determination of potential cave entrance

Determining potential cave entrances is very useful for future crewed or robotic exploration of the red planet Mars. In the HiRISE images, the darker black area represents potentially greater depths where the sunlight is barely reaching. In this region, there is a high probability of having a cave entrance. In general, the special pits exhibit potential cave entrance appearance as a dark linear part in the subset of the darker region by stretching the image contrast. First, the HiRISE darker region should limit its contrast range to low-end radiation values. This image shows a potential cave entrance as a dark area (Cushing et al. 2015).
4 RESULTS AND DISCUSSION:

4.1 Identification of special pit candidates

We surveyed CTX and HiRISE images of the Elysium Mons region and found a lot of impact craters and pits in it. We were interested in finding special pits that looked like they were formed from the collapsed roof of the cave. Such special pits give a much darker look than the normal pits. They also have different morphological and thermal characteristics. An example of the morphological and thermal analysis of pit 22 in this study is shown in Fig. 1. In the middle part of the image, there is a special pit candidate (SP 22). It can be seen that the impact craters in the adjoining areas exhibit crater rays, ejecta, and elevated rim, but the candidate special pit does not show any of these features (Fig. 1 (a)). Again, while in the THEMIS brightness temperature image of evening time, the candidate special pit and impact craters look—alike (Fig. 1 (b)), the special pit candidate shows a warmer appearance than the impact craters and the surrounding areas at midnight (Fig. 1 (c)). Further, it has been found that the SP22 is 4.9K warmer than the surrounding area in the daytime, whereas it is 15.3K warmer than the surrounding area in the nighttime. Also, the diurnal amplitude of temperature variation for SP22 is 10.4 K, which is much lower than the diurnal amplitude of temperature variation of the surrounding area (Fig. 1 (c)). SP 22 shows morphological and thermal characteristics as a special pit; therefore, it is a potential access point of the cave.

Similarly, based on morphological and thermal characteristics, we have identified 32 special pit candidates on the flank of the Elysium Mons (Fig. 2 & Fig. 3). Among them, twenty-six candidates (SP1–4, 6–12, 14–16, 18, and 21–31) are newly found ones, and the remaining six (5, 13, 17, 19–20, 32) are from the Mars Cave database of Cushing & Okubo (2015), Cushing (2015), and Cushing (2019, 2021). The special pits SP1–5, 12–15, 17–27, and 29–31 show a warmer appearance than the surrounding area (a circular buffer zone of radius 500 m) around midnight (11:30 pm to 2:00 am) in the northern summer season (Ls =90–180). Since the midnight data was not available for four special pits (SP 20, 29–31) therefore, they have been observed around 9–10 pm. Their location, elevation, geological context, thermal observations are listed in Table1.
Fig. 1: (a) A CTX daytime image (P02_001989_2077) (location 27.6947, 142.1096) acquired at 10:33 AM; (b) An IRPBT image acquired during the evening at 5:22 PM. (c) An IRPBT image acquired at midnight around 11:34 PM.
Table 1: Morphology, geological context, thermal observation of special pits are given in this table. Here, SP, GU, Hve, IHvf, AGF, LT, TF, and MCC refers to Special Pits, geological units from Tanaka et al. (2014), Hesperian volcanic edifice, Late Hesperian volcanic field, Amazonian and Hesperian volcanic unit, associated geological features, lava tube, tectonic features, and Mars Cave Candidate Catalog (Cushing et al. 2013, Cushing & Okubo 2015, Cushing 2015, 2019, 2021) respectively. Here, if the associated geological feature for a special pit is neither a lava tube nor a tectonic feature, it might be associated with a subsurface Horizontal Magma Conduit (HMC). Additional information, attributes of the special pits such as Perimeter (Pe), maximum length ($L_{max}$), maximum width ($W_{max}$), and depth are tabulated in Table ST1. Here, the special pit’s point location maximum temperature ($T_{max}$) and their surrounding 500 m radius buffer zone mean temperature ($T_{mean}$) have been calculated for the thermal observation time of day (D) and night (N) at the time period of ∼13:00-14:00 and ∼23:30-02:00 respectively. The thermal observation data of night time ∼21:00 to 22:00 has been used in a few cases (SP20, 29-31) where midnight data was not available. The IRPBT data from Mars Odyssey (Christensen et al. 2004, 2017) have been downloaded through the publically accessible web portal - Mars Orbital Data Explorer (ODE) (https://ode.rsl.wustl.edu/mars/) provided by the PDS Geosciences Node at Washington University in St. Louis.

<table>
<thead>
<tr>
<th>Morphology</th>
<th>Identification no., Location, and Elevation</th>
<th>Geological Context</th>
<th>Thermal Observation</th>
<th>Newly discovered Special Pits in this study</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SP</strong></td>
<td><strong>Latitude</strong></td>
<td><strong>Longitude</strong></td>
<td><strong>Elevation (m)</strong></td>
<td><strong>GU</strong></td>
</tr>
<tr>
<td>1</td>
<td>24.4781</td>
<td>11556</td>
<td>Hve</td>
<td>LT</td>
</tr>
<tr>
<td>2</td>
<td>24.4458</td>
<td>11436</td>
<td>Hve</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>24.7341</td>
<td>9912</td>
<td>Hve</td>
<td>LT</td>
</tr>
<tr>
<td>4</td>
<td>24.5934</td>
<td>9208</td>
<td>Hve</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>29.2600</td>
<td>-224</td>
<td>AHv</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>30.585</td>
<td>-2193</td>
<td>AHv</td>
<td>TF</td>
</tr>
<tr>
<td>7</td>
<td>30.5963</td>
<td>-2220</td>
<td>AHv</td>
<td>TF</td>
</tr>
<tr>
<td>8</td>
<td>30.9681</td>
<td>-2532</td>
<td>AHv</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>30.9834</td>
<td>-2547</td>
<td>AHv</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>31.0412</td>
<td>-2551</td>
<td>AHv</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>31.0132</td>
<td>-2555</td>
<td>AHv</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>24.4439</td>
<td>9265</td>
<td>Hve</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>24.7541</td>
<td>8919</td>
<td>Hve</td>
<td>-</td>
</tr>
<tr>
<td>14</td>
<td>24.7602</td>
<td>8706</td>
<td>Hve</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>24.7667</td>
<td>8472</td>
<td>Hve</td>
<td>-</td>
</tr>
</tbody>
</table>
### 4.2 Classification of Special Pits

#### 4.2.1 Morphology

The special pits have been classified into APC I, APC II, and APC III as described in the methodology. As shown in Fig. 2, SP1–11 appear bell-shaped and have overhanging walls and rims; therefore, they are classified as APC I. The APCI are very deep, e.g., SP 5, and SP 6, have calculated depths of ~493 m and ~100 m respectively. The area, perimeter, length, width, and depth of the special pits are tabulated in Table ST1. In the SP12–22, the walls appear to be near-vertical in the upper part; therefore, they are classified as APC II. There is a possibility of overhanging walls in the lower part. The special pits SP23–32 possesses near-vertical walls with the absence of the overhanging walls; therefore, they are classified as APC III. The APC III appears to have heavy dust-covered rubble, e.g., SP 24–31.

<p>| | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>147.5712</td>
<td>7512</td>
<td>Hve</td>
<td>-</td>
<td>D</td>
<td>i55523012</td>
<td>193.2</td>
<td>190</td>
</tr>
<tr>
<td>17</td>
<td>25.5711</td>
<td>146.4503</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>24.4158</td>
<td>4050</td>
<td>Hve</td>
<td>-</td>
<td>N</td>
<td>i54393008</td>
<td>172.9</td>
<td>169.3</td>
</tr>
<tr>
<td>19</td>
<td>25.0786</td>
<td>2438</td>
<td>Hve</td>
<td>-</td>
<td>N</td>
<td>i63217009</td>
<td>206.2</td>
<td>202.8</td>
</tr>
<tr>
<td>20</td>
<td>22.5202</td>
<td>2368</td>
<td>Hve</td>
<td>-</td>
<td>N</td>
<td>i54618008</td>
<td>173.6</td>
<td>168</td>
</tr>
<tr>
<td>21</td>
<td>26.3785</td>
<td>1828</td>
<td>Hve</td>
<td>-</td>
<td>N</td>
<td>i63217009</td>
<td>209.7</td>
<td>205.8</td>
</tr>
<tr>
<td>22</td>
<td>27.6947</td>
<td>710</td>
<td>AHv</td>
<td>-</td>
<td>N</td>
<td>i55698010</td>
<td>201.4</td>
<td>186.1</td>
</tr>
<tr>
<td>23</td>
<td>24.4888</td>
<td>11495</td>
<td>Hve</td>
<td>-</td>
<td>N</td>
<td>i54410018</td>
<td>176.4</td>
<td>169.5</td>
</tr>
<tr>
<td>24</td>
<td>25.1059</td>
<td>2468</td>
<td>Hve</td>
<td>-</td>
<td>N</td>
<td>i63217009</td>
<td>207.8</td>
<td>203.9</td>
</tr>
<tr>
<td>25</td>
<td>20.9777</td>
<td>1842</td>
<td>Hve</td>
<td>-</td>
<td>N</td>
<td>i63217009</td>
<td>210.1</td>
<td>200.8</td>
</tr>
<tr>
<td>26</td>
<td>25.0892</td>
<td>2447</td>
<td>Hve</td>
<td>-</td>
<td>N</td>
<td>i63217009</td>
<td>214.2</td>
<td>203</td>
</tr>
<tr>
<td>27</td>
<td>26.8415</td>
<td>1072</td>
<td>IHvf</td>
<td>-</td>
<td>N</td>
<td>i55698010</td>
<td>194.9</td>
<td>187.3</td>
</tr>
<tr>
<td>28</td>
<td>19.8542</td>
<td>667</td>
<td>AHv</td>
<td>-</td>
<td>N</td>
<td>i63246013</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>29</td>
<td>22.9848</td>
<td>186</td>
<td>AHv</td>
<td>-</td>
<td>N</td>
<td>i63809022</td>
<td>193.2</td>
<td>187.2</td>
</tr>
<tr>
<td>30</td>
<td>22.9114</td>
<td>129</td>
<td>AHv</td>
<td>-</td>
<td>N</td>
<td>i63809022</td>
<td>190.9</td>
<td>187.4</td>
</tr>
<tr>
<td>31</td>
<td>22.9058</td>
<td>124</td>
<td>AHv</td>
<td>-</td>
<td>N</td>
<td>i63809022</td>
<td>194.6</td>
<td>188.2</td>
</tr>
<tr>
<td>32</td>
<td>30.5613</td>
<td>-1522</td>
<td>AHv</td>
<td>-</td>
<td>N</td>
<td>i54362025</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**APC III**
4.2.2 Geological context

This study shows that two special pits SP 1 and 3, are associated with lava tubes rille structure (Fig. 4 a, b); therefore, they are considered as lava tube special pits, whereas two special pits SP 6 and 7 are associated with Tectonic Features (Fig. 4 c, e) therefore considered as Tectonic Feature special pits. The rest of the special pits are located on a volcanic flank but are not associated with Lava Tube and tectonic features; therefore, they are classified as Horizontal Magma Conduit (HMC) special pits. e.g., three special pits SP13, SP14, and SP15. They are arranged in a linear array (Fig. 5). It is possible that they may be related to the horizontal spread of magma through a flank conduit. The SP 22 is located on a lava plateau, so it may be associated with the HMC. At the same time, it also has a nearby tectonic feature indicating that tectonic activity also contributed to the formation of this HMC special pit.

4.3 Determination of Potential Cave entrance

CTX images (Fig. SF1 (a) & Fig. SF1 (b)) from different sun incidence angles (Table ST2) of the special pit candidates have been studied on the flank of the Elysium Mons. In all the images, the studied candidates exhibit morphological characteristics of special pits. At different sun incidence angles, the shadowed portion of the special pit candidates gets reduced or enhanced; however, it has been observed that a portion of the special pit candidates consistently appear dark in all the images suggesting that this constantly dark appearing area is very deep where sunlight does not reach. It is very likely that the cave entrance is present in this dark zone.

The determination of potential cave entrance is possible using HiRISE images (Fig. 6 & Table ST3) due to its very high spatial and radiometric resolution. In this study, investigation for potential cave entrance has been attempted for nine special pits for which HiRISE images were available. As shown in Fig. 6, a subset of the shadowed part in the contrast stretched HiRISE images is delineated by the red boundary. The long shadows beneath the layers indicate an 'overhang' where possible entrances to a cave may occur as other entrances are not detected elsewhere in the walls of the pits at the current image resolution. In this region, there is a high probability of the presence of a cave entrance. The SK 5, 13−15, 17, and 19−20 exhibit potential cave entrance in the form of a dark linear part indicated by a white arrow (Fig. 6). The gray and relatively white areas are shallower regions on the potential cave floor where the scattered sunlight is reaching. The reduction of depth in these areas of the potential cave floor may be due to the presence of talus and/or dust material of varying thicknesses. The white areas have a thicker pile compared to the gray areas. In most of these cases, the white area is also found at the edges of the subset since the light directly reaches the edges or the side of the upper walls.

The SP 28 and SP 32 exhibit potential cave entrance in the form of a continuous shadowed pattern. The white pattern is visible at the edges of the upper walls with a continuous shadow pattern on the potential cave floor which indicates that the upper roof of the rock shelter has suddenly collapsed or a huge amount of dust has fallen. In SP 5, heavy talus material has been observed as a white pattern in the west and south—west direction, while gray shade indicates irregular collapse material on the potential cave floor during different times. The SP14 and SP 19 have a pile of talus material in the SW and western direction denoted by a white dotted scattered pattern. Comparatively less, SP15 has a pile of talus material in the NW and western directions. In SP 19, the darker region has been present in NW and West direction as it is indicative of higher depth, while the subset of the darker region in an enclosed box on the left side is indicative of the irregular pile of talus material and dust at the potential cave floor within overtime. Thus, the HiRISE image investigation also indicates the evolutionary stage of special pits by providing evidence for the presence of dust and talus material on the potential cave floor.
5 CONCLUSIONS

In this study, thirty-two special pit candidates on the flank of Elysium Mons on Mars (Fig. 7) have been classified on the basis of morphology and geological context. Out of these, twenty-six special pit candidates (SP 1–4, 6–12, 14–16, 18, and 21–31) are newly identified ones. Among all, based upon their morphology, eleven candidates (SP1–11) have been classified as APCI, eleven candidates (SP12–22) as APCII, and ten candidates (SP23–32) as APCIII. Two of the special pit candidates are associated with lava tubes and two with tectonic features; therefore, they are considered as Lava Tubes special pits and Tectonic Feature special pits, respectively. Others could be associated with Horizontal Magma Conduits. Consequently, they have been classified as Horizontal Magma Conduit – special pits. Besides their geological setting, the potential cave entrances have been worked out for the candidates for which HiRISE data was available. Our thermal investigations have revealed that the special pits identified in this study are radiating heat at night, similar to the potential caves. Thus, the special pit candidates in this study could be suggestive of possible caves on the flanks of Elysium Mons, which could be essential destinations for future human/rover missions as well as the search for life on Mars.

Acknowledgements The science and engineering teams of MRO, MGS, and Mars Odyssey are thankfully acknowledged for providing imaging, topography, and thermal data through publicly open web portals. We thank Varun Sheel, S.A. Haider, and Anil Bhardwaj, Director PRL, Ahmedabad, India, for providing encouragement and the necessary facility to carry out this work. We also gratefully acknowledge the reviewers for their useful comments and suggestions that have significantly improved the manuscript.

References

Barker, D. C., James, G., Chamitoff, G., & Clifford, S. 2015, in LPI Contributions, Vol. 1879, First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars, 1002
Boltzmann, L. 1974, The second law of thermodynamics (Springer), 13
Boston, P., Frederick, R., Welch, S., et al. 2003b, Gravit. space biol. bull., 16, 121
Cigna, A. A. 1968, International Journal of Speleology, 3, 3
Coblentz, W. W. 1925, Astronomische Nachrichten, 224, 361
Cushing, G. 2012, Journal of Cave and Karst Studies, 74, 33
Cushing, G. 2015, Mars Global Cave Candidate Catalog PDS4 Archive Bundle. PDS Cartography and Imaging Sciences Node (IMG)
Cushing, G. 2019, Mars Global Cave Candidate (MGC~3) v1 cushing,USGS Astrogeology Science Center
Cushing, G. 2021, Mars Global Cave Candidate (MGC~3) v1 cushing, USGS Astrogeology Science Center, https://astropedia.astrogeology.usgs.gov/download/Mars/MarsCaveCatalog/mars_cave_catalog.zip
Potential caves on the flank of Elysium Mons, Mars

Davila, A., Fairén, A. G., Rodríguez, A. P., et al. 2015, in LPI Contributions, Vol. 1879, First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars, 1012
Fergason, R. L., Christensen, P. R., & Kieffer, H. H. 2006, J. Geophys. Res. Planets, 111, E12004
Sharma, R., & Srivastava, N. 2021, Earth and Space Science Open Archive (ESSOA), 25
Wright, S. P., Niles, P. B., Bell, M. S., et al. 2015, in LPI Contributions, Vol. 1879, First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars, 1017
Fig. 2: A view of the thirty-two special pits using CTX/HiRISE images. SP1–11, SP12–22, and SP23–32 have been classified into APC I, APC II, and APC III respectively.
Fig. 3: A view of the THEMIS IRPBT images of twenty-three special pits. The SP 6–11, 16, 28, and 32 are less than 100m in diameter therefore their thermal behavior could not be studied.
Fig. 4: A view of the geological features associated with special pits. (a) A rille associated with SP1 and presence of SP2 and SP23 in the nearby area; (b) A rille associated with SP 3; (c) SP 22 is located on a lava plateau, adjacent to a tectonic feature.; (d) a large crater associated with SP8, 9, 10, and 11; (e) A tectonic fracture associated with SP 6 and SP 7; and (f) A dune covering volcanic field associated with SP 28.
Fig. 5: (a) Elevation map of the Elysium Mons region using MOLA and THEMIS IR day images in the background showing the location of the special pit (SP13, SP14, and SP15); (b) Close-up view of the area enclosed by the black box in subsection (a). Here, the individual special pits are enclosed by a red box; (c−e) A close-up view of the individual special pits. The sub-sections (c) & (d) have been prepared using HiRISE images, while a combination of HiRISE (left side) and CTX (right side) data has been used for depicting a close-up view of the third special pit (e).
Fig. 6: The contrast stretched HiRISE images of special pits (5, 13−15, 17, 19, 20, 28, and 32). The shadowed area in the original panchromatic images is enclosed by a red polygon. The white arrows show the potential entrance for the associated potential caves in each of these cases.
Fig. 7: An elevation map of Elysium Mons, Mars from MOLA data showing the location of the thirty-two special pits studied here. The red stars, green dots, and blue triangles symbol correspond to those classified as APCI (SP1–11), APCII (SP12–22), and APC III (SP23–32), respectively. Out of thirty-two special pits, twenty-six SP (SP 1–4, 6–12, 14–16, 18, and 21–31) are newly discovered ones. The name of the geological location is indicated by the label with a yellow pin.