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A STUDY ON THE MORPHOLOGY AND GEOLOGY OF DULOVO CRATER; SOUTHERN LIBYA MONTES, MARS

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Abstract

Dulovo crater is located at the border of Libya Montes and surrounded by Isidis Planitia to the North and Terra Tyrrhena to the South, with Syrtis Major Planum to the West. This is a region affected by impact, volcanic, aeolian, and fluvial processes. The aim of this study is to identify the geomorphological and geological units in the Dulovo crater Southern Libya Montes, Mars. For this reason, we prepared a 1:100,000 scale geomorphology map of the study area, applied remote sensing methods to determine the mineral content of rocks and used crater-size frequency distribution (CSFDs) to determine the age of the meteor impaction. The geomorphological units observed in the Dulovo crater are highly altered ejecta, proximal ejecta plain, proximal altered ejecta plain, craters, valleys, debris flows, crater rim, floor sediments, altered floor, sand dunes and crater mound, which represent inactive or ongoing processes on Mars. The spectral mineralogy analysis show that the area consist of pyroxene-olivine rich rocks, pyroxene rich bedrocks, pyroxene rich caprocks (allochthon), a few phyllosilicate-rich outcrops and olivine-rich outcrops. Finally, CSFDs method has been applied to the crater ejecta and yielded an age of 3.74 ± 0.06 Ga that represents the timing of the meteor impact.
Keywords: Dulovo crater, Spectral mineralogy, Libya Montes, geomorphology, pyroxene-olivine rich rocks, CSFDs.

DULOVO CRATER'İN MORFOLOJİSİ VE JEOLOJİSİNİN ARAŞTIRILMASI; SOUTHERN LIBYA MONTES, MARS

Öz

Dulovo krateri, Kuzey'de Libya Montes ve Isidis Planitia ile güneyde Terra Tyrrhena'nın sınırında, Syrtis Major Planum un Batı'sında yer alır. Burası, meteor çarpmaları, volkanik, rüzgar ve flüviyal süreçlerden etkilenen bir bölgedir. Bu çalışmanın amacı, Mars'ın Libya Montes bölgesinde bulunan Dulovo kraterindeki jeomorfolojik ve jeolojik birimleri tanımlamaktır. Bu nedenle, çalışma alanının 1: 100.000 ölçekli jeomorfoloji haritası hazırlamış, kayaçların mineral içeriğini belirlemek için uzaktan algılama yöntemleri uygulanmış ve meteor çarpmasının yaşını belirlemek amacıyla krater boyu frekans dağılımı (CSFD) kullanılmıştır. Buna göre, Dulovo kraterinde gözlemlenen jeomorfolojik birimler, çok ayrışmış ejekta, yakınsak ejekta düzlüğü, yakınsak ayrışmış ejekta düzlüğü, çarpma kraterleri, vadiler, moloz akıntıları, krater kenarı, taban çökelleri, ayrışmış krater tabanı, kumul tepeleri ve krater tepeleridir. Bu yapılar Mars üzerindeki geçmiş ve sürmekte olan süreçleri temsil ederler. Spektral mineraloji sonuçları ise çalışma alanının piroksen-olivin zengin kayaçlardan, piroksen açısından zengin temel kayaçlardan, piroksen bakımından zengin allokton kayaçlardan, birkaç adet filosilikat bakımından zengin mostralar ve olivin bakımından zengin mostralardan oluştuğunu göstermiştir. Son olarak, krater ejektasına CSFDs yöntemi uygulanmış ve 3.74 ± 0.06 Ga yaşını vermiştir. Bu yaş meteorun çarpma zamanını temsil etmektedir.
Anahtar Kelimeler: Dulovo krateri, Spektral mineraloji, Libya Montes, Kumul tepeleri, piroksen-olivince zengin kayaçlar, CSFDs

1 Introduction

Mars can be described as a red planet that contains many unknown areas that are slowly discovered by continuous research efforts. Investigations particularly focus on finding places with potential water sources, suitable atmospheric conditions and other crucial logistic needs that will facilitate building a colony on Mars. Therefore mapping the planet's geologic and geomorphic aspects is essential. Today, rovers sent to Mars are supporting these efforts by providing direct field observations. However, in order to run properly such instruments on Mars they need to land safely on the planet. Craters are commonly preferred as landing sites because of soft sediments that cover the crater floor. Hence mapping craters is an important step in discovering the red planet.

In this context, we choose the Dulovo crater as our study site and mapped the crater at 1:100.000 scale (Figure 1). We identified different types of geomorphological structures within the crater and obtained a highly detailed geomorphology map. Besides, we analysed the mineral content of surrounding rocks to constrain their geological nature. Finally, we calculated the timing of the crater impact.

2 Methodology

In this study, we applied remote sensing mapping techniques using the images of different satellites that operated around Mars. High resolution stereometric camera (HRSC; 12.5 m/pixel), Context Camera (CTX; 6m/pixel), High Resolution Imaging Science Experiment (HiRISE; 0.3m/pixel), Compact Reconnaissance Imaging Spectrometer (CRISM; pyroxene/olivine) satellite images and digital terrain models were used to document geomorphic structures such as sand dunes, craters, crater ejecta blankets, crater mound and canyons (Table 1).

2.1 HRSC Images and Digital Terrain Models

The Mars Express satellite has a HRSC instrument, which is capable of taking nearly simultaneously high-resolution stereo, multicolour, and multi-phase angle superimposed image swaths (Figure 1c). The image resolution of the HRSC is radiometrically calibrated, geometrically corrected and has a resolution of 12.5 m/pixel. The digital elevation data (HRSC-DTM) has a resolution of down to 50 m/pixel and a vertical accuracy at 10 m/pixel. These images are used to determine photometric surface characteristics and to create digital terrain models (DTMs) (Figure 1b) [18].

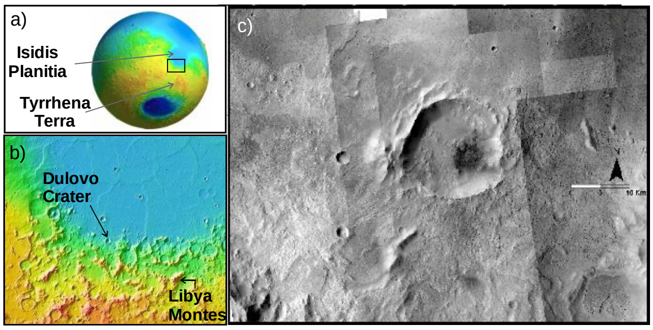


Figure 1. a) The Dulovo crater is located at the southern limit of the Isidis Planitia (black box), b) HRSC image of the Dulovo crater. The dark area within the crater corresponds to sand dunes (Figure 2).

2.2 CTX (Context Camera) Images

The CTX provides images that are simultaneous records of the HiRISE and CRISM spectrometer. The CTX is imaging 400km above Mars and provides a wider coverage compared to other instruments. The camera has 6 meters per pixel resolution. HiRISE, CRISM, and CTX are extremely useful to investigate Mars surface conditions. For instance, most of the stratified morphologic units discovered on the Mars were studied with the Orbital Camera. CTX images allow differentiating meteor impactions, canyons, volcanic lavas, ash or wind bed sediments. In our analyses, we used CTX image data to map and visualize the Dulovo crater and determine its geologic characteristics.

2.3 HiRISE Images and DTMs

High Resolution Imaging Science Experiment (HiRISE) images are acquired via 14 CCD detectors, each with multiple choices for pixel binning and number of time delay and integration lines [11]. Therefore, the HiRISE instrument is capable of getting 0.3 m high-resolution images and near-infrared wavelengths that allow obtaining information on the mineral groups. The image is extremely powerful to differentiate 1-meter-size objects on Mars and to check the geomorphology in an exceedingly comprehensive way compared to other satellite instruments (Figure 2).

2.4 CRISM Images and Spectral Data

The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) collects ~10 km wide images from 0.4 to 3.9 mm at ~18 m/pixel in the full resolution targeted (FRT) mode and at ~36 m/pixel in the half-resolution short or long mode [15]. These high-resolution CRISM data are used to interpret the mineral content of the Dulovo crater by looking at the spectrometric differences (Figure 6).

2.5 Crater-size Frequency Distribution Method

Digital geomorphic mapping and CSFDs has been performed using CTX image and digital terrain data as base maps with ESRI ArcGIS software and Craterstat2 and CraterTools plugins [4]. We worked with a mapping scale of 1:100,000 and used an HRSC digital terrain model as base map (50m/pixel) of this region. The method of our mapping techniques mostly follows the methods explained in references [2-7].

The CSFD method has been applied to obtain an absolute age for the crater impaction. The method is based on the correlation of the number of impacts on a surface at a given diameter (crater-size frequency) to a known crater production function. The calculation of an absolute age is possible because the frequencies can be calibrated with radiometrically dated samples from Moon and Mars [13]. The method produces a minimum age or resurfacing age for the geologic units [13]. We preferred to use a chronology function [5] and production function [6] and the chronological epochs of [12]. Crater mapping and measurements were performed with HRSC images [10]. Additionally, the "craterstats2" software tool was used to obtain the plots of the crater density analysis [13]. Only craters over 100 meters in diameter were used in the calculations.

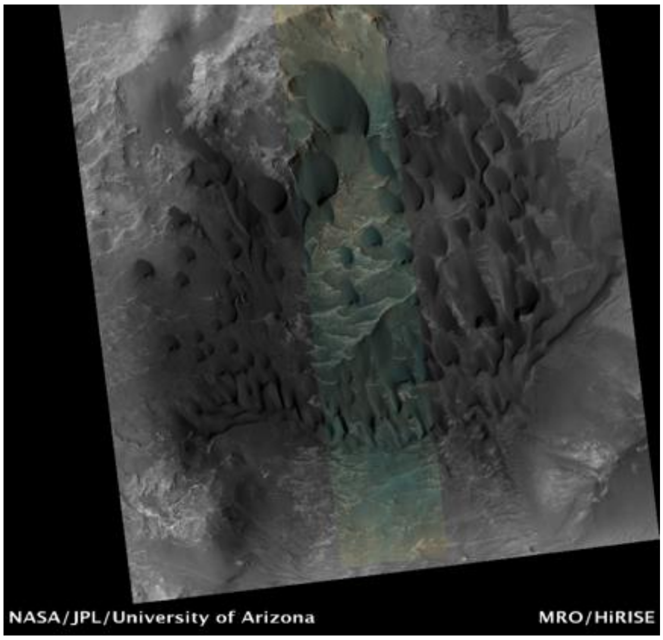


Figure 2. HiRISE satellite image of sand dunes located in the Dulovo crater.

3 Literature

3.1. Mars Exploration

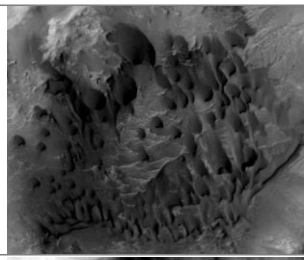
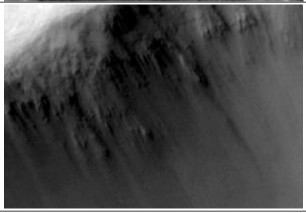
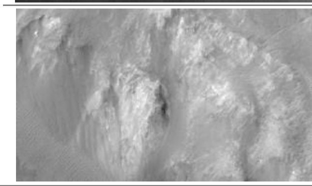
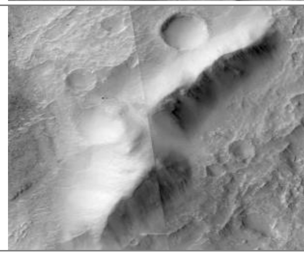
Before the 20th century, Mars was discovered through man's imagination or fiction. In the last century, studies of our solar neighbours got a big hold. Mariner 9 began successfully operating in 1964 with NASA's leading Mars researches. In addition to this, the Mars Exploration Rovers (Spirit and Opportunity), the Mars Express, the Mars Observer, the Mars Pathfinder, the Mars Climate Orbiter, the Mars Polar Lander / Deep Space 2, the Mars Global Surveyor and Mars Odyssey and Mars Atmosphere and Volatile Evolution (MAVEN) exploration missions were launched consecutively. Scientists have begun to study the red planet, especially with the data obtained in 1991, and in the following years new findings allowed to build hypotheses on the geological evolution and life on Mars.

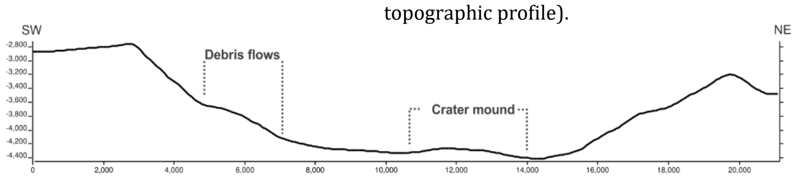
3.2. Libya Montes

Libya Montes is a well-known and covered (in terms of satellite images) area which many researchers are working on [1, 9, 19]. It has a distinct geomorphic characteristic compared to other parts of Mars with very complex valley systems that originate from lava flow related structures and fluvial systems. From West to East the region shows a change of volcanic topography to a fluvial terrain. The first study in the region provided a classification and a map of the geomorphological units of Libya Montes (Figure 3) [2]. According to this study, Libya Montes consists of the following units:

- *Noachian massif (Nm),*
- *Noachian bedrock,*
- *Noachian/Hesperian fluted and dissected terrain (nhf),*
- *Fluvial dissected bedrock,*

Table 1: Description of mapping methods for some of the geomorphological units.

Geomorphological Unit Name	Mapping method	CTX images of the geomorphological units
<u>Sand Dunes</u>	The main reason for the different mapping of sand dunes is to recognize the colours and structures by satellite images.	
<u>Debris Flows</u>	These structures, which are thought to be debris flows detected by using slope map of satellite images, are bounded and mapped by topographic profiles along the hillside (see topographic profile).	
<u>Crater Mound</u>	Were mapped as crater mounds detected by elevation differences due to the profiles taken along the crater (see topographic profile).	
<u>Nh_Highlands</u>	Mapped according to the detailed satellite images of the region compared with the digital elevation models of other geomorphologic units located outside and surrounding the Nh_higlands.	



- *Hesperian/Amazonian eroded material (hae),*
- *Heavily degraded material,*
- *Aeolian erosion material,*
- *Partial remnants of lava flows,*
- *Noachian/Hesperian/ Amazonian valley deposits (nhavd) (no absolute ages),*
- *Lava deposits*
- *Ejecta blanket of meteor impact.*

According to their observation, Libya Montes and the southern Isidis region consists of a dense valley network, which cuts into the terrains of Noachian, Hesperian and Amazonian periods. Other studies suggest a similar evolution for the Isidis region where an impact-dominated episode (Noachian to Early Hasperian) was followed by an episode by volcanic and fluvial/glacial activities (~3.8–2.8 Ga) [7]. The eastern part of the Libya Montes is a dusty terrain with sediments of extremely different mineral composition as suggested from surface thermo-physical inertia measurements [14]. Nevertheless, there are still dust-free surface outcrops of olivine and pyroxene-bearing lithologies [1].

4 Characteristics of the Dulovo Crater

We studied the physical parameters, geomorphology and mineralogy of the Dulovo crater region with multiple data sets as given in the methodology section. The crater is located at ~ -4000m elevation at the southern limit of the İsidis basin. It has a diameter of 17.7 km, reaches a depth of ~1600 m and is surrounded by a 230 m high rim. The inner crater floor is approximately 6 km wide (Table 2).

4.1. Geomorphology

The morphology of Dulovo crater can be divided into two domains, the inner crater and the outer crater. **Outer crater** geomorphological units consist of (Figure 4, Table 1):

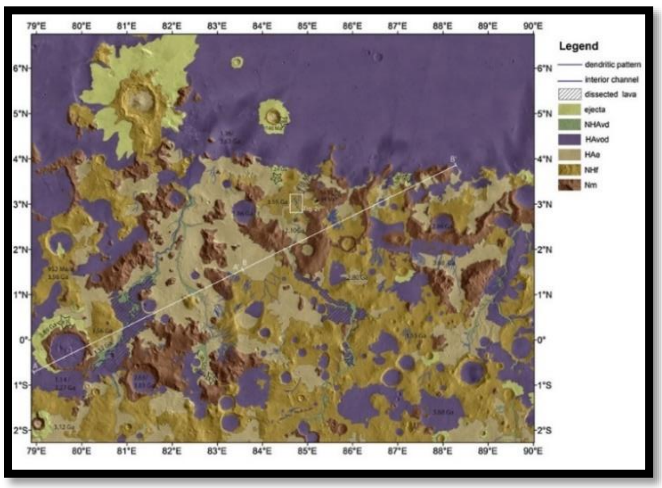


Figure 3. The geomorphological map of the Libya Montes adapted from Crumper and Tanaka 2003.

1- **Noachian-aged highly altered ejecta:** The oldest units mapped within the outer crater are the Noachian highland basements characterized by massive mountains. They appear as gently dipping hills with a rugged surface or mountain chains with relatively steep slopes and sharp crests. These structures represent high topographies prior to the meteor impaction [2]. The overall age range of these units in the Libya Montes is known as 3.98 to 3.45 Ga [1, 2].

2- **Basement rocks:** represent the terrain prior to meteor impaction.
3- **Proximal ejecta plain:** Is a group of sediments that are extruded out from the meteor crater during the impact stage and deposit around the external area of a crater [3].
4- **Craters:** Are circular depressions, which are formed after the main meteor impaction and represent the impacts of other small bodies around the crater area [3].
5- **Valleys:** Are large-scale gorges or canyons with steep rocky walls. They truncate ejecta plains, basement rocks and crater rim.

The **inner crater** contains (Figure 4):

1- **Debris flows:** Are loos masses of mud, sand, soil, rock and liquid that travels downhill the crater's inner slopes due to gravitational forces [14].
2- **Crater rim:** Refers to the circular or elliptical edge that represents the uppermost tip of the raised portion of the crater [4].
3- **Floor sediments:** are sediments that derive from the inner slopes of the crater and deposit in the centre of the crater [4].
4- **Altered floor sediments**: Are highly weathered floor sediments.
5- **Sand dunes:** Are hills of loose sediments built by aeolian processes consistently acting in specific directions [14]. In the Dulovo crater, sand dunes are barchans and indicate a wind direction from NW to SE.
6- **Crater mounds:** are remnants of an extensive sequence of deposits that survived the meteor impact [3].

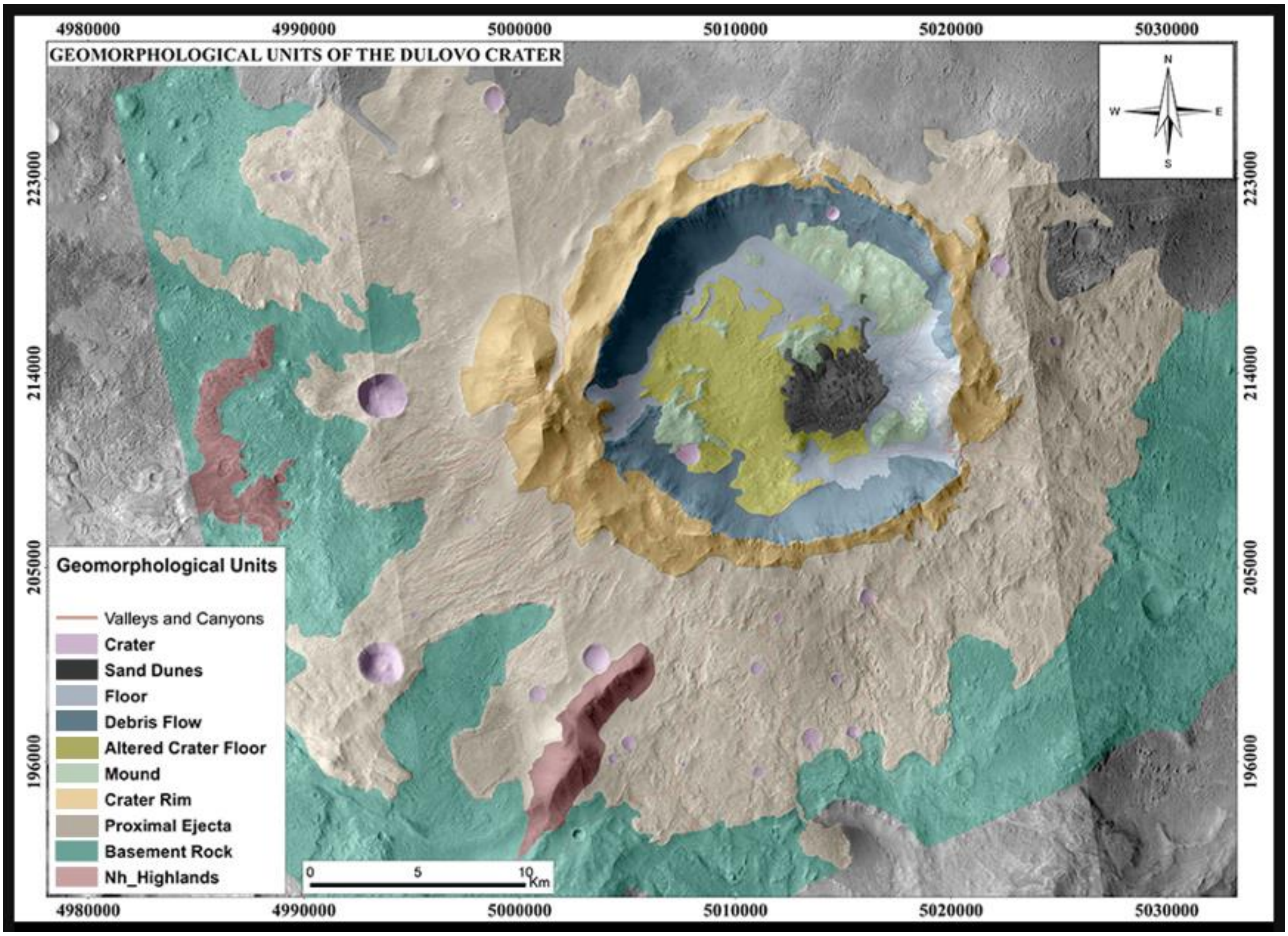


Figure 4: The Dulovo Crater is a meteor impact crater that has a diameter of 17.7 km. Several morphological have been mapped within and outside of the crater.

Table 2. Physical parameters of the Dulovo crater (*D:* crater diameter, *Rim*: height of rim: *d*: depth (crater's lowest to highest point), *Dt:* transient crater diameter, $_c$***Rim***: distance of ejecta to rim; calculated after [22], ***Ejecta:*** approximate ejecta height, ***Central uplift***: mound height).

Location	*D* (km)	Rim (m)^{b2}	d(m)^{b1}	*d* (m)^{b2}	*d* /*D*	D_t(km)	$_c$Rim (m)^c	Ejecta (m)	Central uplift (m)
84.6°E 3.6°N	17,7	371	~1500	~1672	0.070	8.9–12.4	~451	625-1039	~180

a = measured; i.e., measurements of the rim based on the MOLA DEM.
b1 = Measurements of crater depth based on the HRSC DEM.
b2 = Measurements of crater depth based on the CTX MOLA DEM.
c = calculated; i.e., calculated rim height based on the equations of [22].

4.1. Spectral Mineralogy

Spectral mineral analyses were applied to evaluate the mineralogical properties of rocks within and around the crater. We used the CAT (CRISM Analysis Tool Kit) software; the predefined band combinations within the program enhances mineralogical differences of the rocks [23]. The results are comparable with previous studies at Dulovo crater [1, 2] (Figure 5).

The theory behind the investigation of minerals by spectral analysis are crystal lattice vibrations in minerals
results from photon interactions that modify the spectral signal of the material in different shapes [20]. Hence, the sand dunes consist of olivine-pyroxene minerals. The pyroxene is well correlated with low albedo and relatively dust-free regions located both in the Libya Montes rim and in the Isidis Basin in the western part of our study region [1]. Although the actual source is unknown, the material is distributed almost all over Mars by globally acting aeolian processes [20]. Besides, we determined that within the Dulovo crater bedrocks are pyroxene rich, caprocks are pyroxene rich, and outcrops are phyllosilicate-rich and olivine-rich (Figure 5).

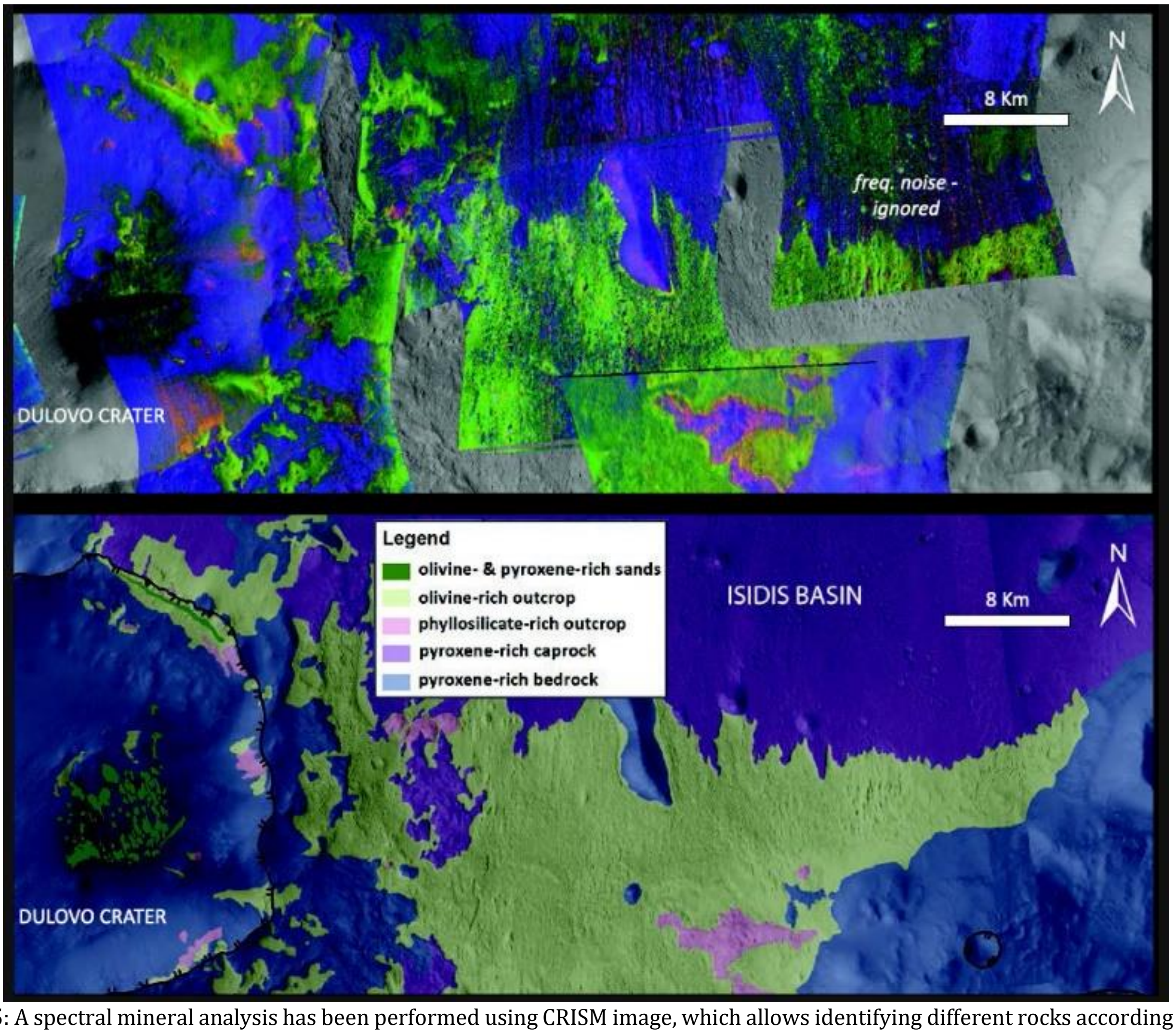


Figure 5: A spectral mineral analysis has been performed using CRISM image, which allows identifying different rocks according to their mineral content (top). We mapped five type of rocks that show different crystal lattice vibrations (bottom).

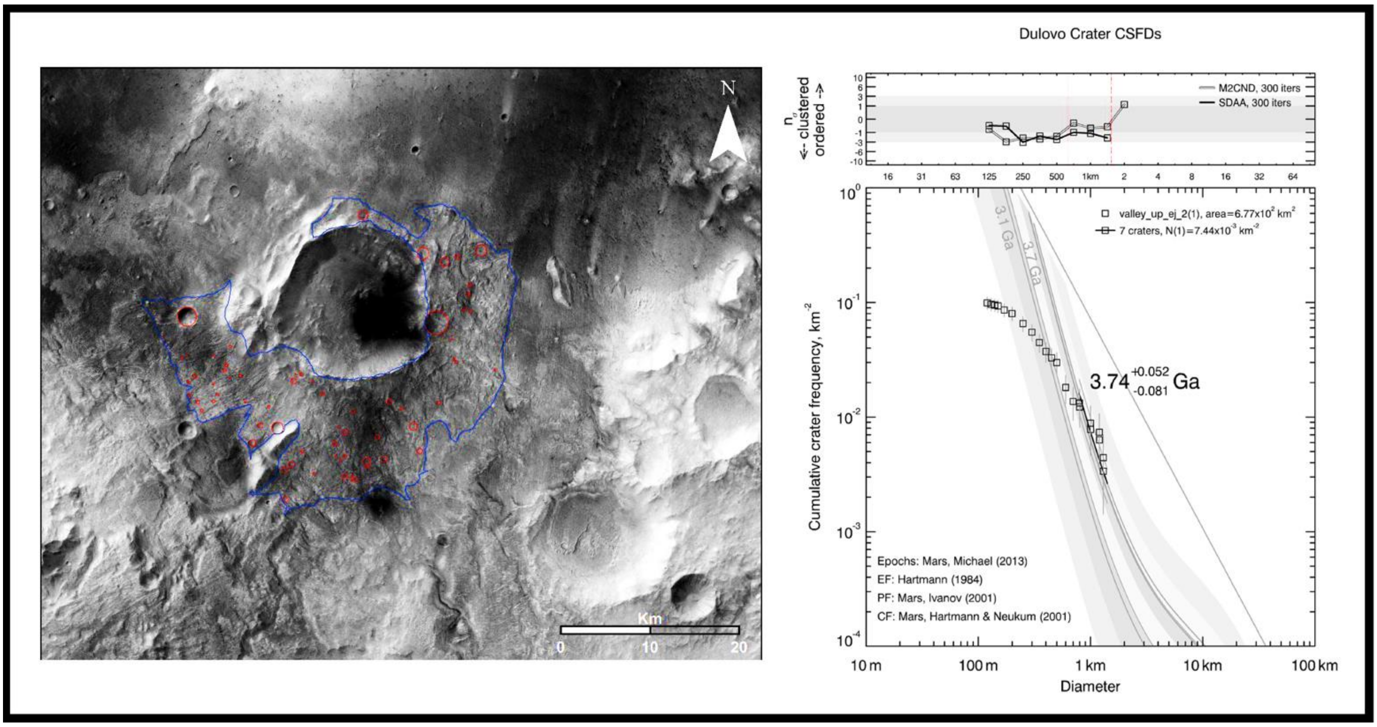


Figure 6: Crater size-frequency distribution (CSFDs) measurements of the Dulovo crater units. Left: Counted craters marked with red circle. We use the production function and chronology function from [6] and [5], respectively.

5 Chronology of the Dulovo Crater

We applied crater-size frequency distribution method (CSFDs) to date the proximal ejecta of Dulovo Crater (Figure 6). Fifty craters with minimum 100 m diameter and not effected by resurfacing events have been counted. The absolute distribution of counted craters and the cluster ratings are calculated and displayed on the plot using the "craterstat2" software [13].

As a result, the age of the proximal ejecta of the Dulovo crater is 3.74 ± 0.06 Ga.

6 Results and Discussions

The geomorphological, mineralogical and chronological study reveals the main geomorphological setting of the Dulovo crater. According to our mapping, we distinguished the following units:

Outer crater area:

1- Noachian-aged highly altered ejecta
2- Basement rock
3- Proximal altered ejecta plain,
4- Craters,

Inner crater area

1- Valleys and Canyon,
2- Debris flows,
3- Crater rim,
4- Floor sediments,
5- Altered floor,
6- Sand dunes
7- Crater mound structures.

The units are mapped at 1:100.000 scale. The map provides for the first time significant geomorphic details about the crater and surrounding area.

The spectral mineral analysis reveals that within the crater, bedrocks are pyroxene rich, caprocks are pyroxene rich, and outcrops are phyllosilicate-rich and olivine-rich. The distinct sand dunes in the crater are composed mainly of pyroxene and olivine. Their barchans like structure signifies a dominant NW to SE wind direction. Our findings are compatible with earlier studies that suggest that Libya Montes is made from an old basalt unit [1].

The CSFDs measurement in the Dulovo crater demonstrates the absolute age of the meteor impaction as 3.74 ± 0.06 Ga.

According to the M2CND and SDAA quality evaluation methods and resultant randomness analysis diagram, craters with 530 to 1600 km are providing reliable results for age determination because they fall in -1 and 1 limit (Figure 6 top). Other craters within the limit are excluded because they are close to the >100 m criteria. This selection improves our accuracy in the age. Since the acceptable error range for this method is ± 0.1 Ga our age error range of ±0.06 is highly reliable.

The age of the Dulovo crater corresponds to Mid-Late Noachian. The timing of the crater suits the period when large meteor impaction occur and form the Isidis basin [21]. Besides, the existence of pyroxene and olivine rich rocks is in accordance of the Fe and Mg rich period; in which hydrated silicates are dominant [21]. Currently the Dulovo crater is exposed to erosional and depositional processes. Valleys, canyons and debris flows occur at the inner slopes of the crater, while floor sediments and sand dunes deposit in the central part of the Dulovo crater. Crater impactions continue to occur.

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