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RESEARCH ARTICLE

Topographical Analysis of Lonar Crater Using Cartosat-1 DEM

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Abstract The Lonar crater in India provides an ample opportunity to in-depth analysis of crater morphology. This paper focuses on the topographical mapping of Lonar crater with detailed study on slope, regional analysis and its rim signature. The slope of the crater (inner wall region) reveals that the northern part is steep and southern part is gentle, while, on the outer region, the northern part is flat and the later shows abrupt variations. On regional topographical mapping (~4 crater radii) around the Lonar crater, it was observed that the terrain descends from NE to SW. An elevation difference of ~20 m was observed between the N and S part, infers that the pre-impact terrain is a descending one. The crater northern rim was elevated ~10 m to ~15 m, whereas southern rim was elevated ~50 m above the average regional surface. We found that the topographically lower southern region was abruptly changed and the rim has been uplifted to an elevation of ~604 m above the average regional elevation (~555 m). This result infers that the post-impact topography was abruptly altered along the S side. The crater rim signature extracted from highest point all along the rim shows a near flat surface on north, whereas the V-shaped protrusion shows active erosion and degradation on the west. Thus, DEM based topographic study has opened a new insight about the Lonar crater, from differential rim uplift, alteration along the rim and finally revealed that the impact crater formed on a descending terrain.

Keywords Crater · Topography · DEM · Lonar

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Introduction

The Lonar crater in India is one of the impact craters that the Earth retains and this crater belongs to the simple class crater. On the Earth, several impacts have occurred over different target (rocks) at different time intervals. Mostly, the craters have been degraded due to the Earth's active weather/tectonics but some had retained their morphology. Impact craters are the dominant surface features on planetary surface especially on the moon. But, earth retains only fewer craters when compared to other planetary bodies. On the Moon, the craters are the dominant surface features (Neukum et al. 1975; Heiken et al. 1991) which are distributed in almost all parts and in all sizes. Terrestrial craters have been studied (Fredriksson et al. 1973; Melosh and Ivanov 1999; Kring 2007) to understand their surface, target material, topography, ejecta and all other crater related events. The topography of the crater alters from initial stage to its final stage. The pre-impact landscape will be abruptly varied depending on the impact object size and velocity. Higher spatial elevation data are currently available, which helps in understand the crater better. These data are helpful in exposing the unexplored history of the craters on detailed analysis. Terrestrial crater study will lead to understand the extra-terrestrial impact craters on several aspects. Validation of the discriminated objects on Earth's surface can be done in situ, while for extra-terrestrial, there are fewer possibilities of in situ experiments. In such instances, insitu experiments on terrestrial will aid in understanding the extra-terrestrial bodies. Hence, for this study the Cartosat-1 stereo pair data set was used for analysing Lonar crater topography. This, DEM based regional topography study has revealed the differential uplift in the Lonar crater.

Lonar Crater

Lonar crater (Fig. 1a) was formed on the layered basaltic lava formations of Deccan traps, India. Several lava flows had formed the Deccan traps. Five such flows are exposed on the top-most inner wall of the crater (Fredriksson et al. 1973; Fudali et al. 1980; Geological Survey of India (GSI) 1993; Kumar 2005). The significance of this crater is well known because of its target rock i.e., basalt, which is also the prominent litho-unit of the Lunar mare surface (Heiken et al. 1991). The centre of the crater has been converted into a lake with water inflow from the surrounding region, especially from the NE side. Several authors have studies Lonar crater (Kumar 2005; Osae et al. 2005; Maloof et al. 2010) but most of the studies pertain to a local region only. This study analyzes the topographical changes happened in and around the crater on a regional basis.

Rim uplift and bedrock upturn is common phenomenons that happen in most of the craters. Normally, crater studies carried out on-field (Maloof et al. 2010) or by simulation (Oberbeck and Quaide 1967; Head et al. 2002; Collins et al. 2004; Senft and Stewart 2007) consider the craters only and not their surrounding terrain. Since, they are assumed to be part of a flat surface. But it need not be always flat, as in the case of Lonar (which is formed on a descending terrain). Therefore, the major goal of this study is to explore the topographical changes around the Lonar crater from rim uplift to regional variations. Thus, the Lonar crater provides an ample opportunity to study the impact effects on the descending target topography.

Cartosat-1 Data Set

Cartosat-1 panchromatic (0.5–0.85 μm) stereo pair image (2.5 m resolution) acquired on 12 May 2008 was used for the extraction of DEM. Cartosat-1 has two panchromatic solid-state cameras, one camera looks at +26 ° forward (Fore) while another looks at −5 ° backward (Aft) to acquire stereoscopic imagery with a base-to-height ratio of 0.62. The fore-and-aft images were co-registered with 9 GCPs (ground control points) obtained from the Survey of India topographic maps. Twenty four tie points were selected in the image to minimize the elevation errors in DEM. The Y-parallax error for the tie points was 0.90. For the stereo pair, the tie points and the regional elevation data were given as input and the digital elevation model (DEM) (Fig. 1b) was generated using the triangulation technique. The RMS error for the DEM is ~8 m. The central portion of the lake which contains water was masked to an elevation of 475 m to avoid artifacts. After the generation of the DEM, the outline of the crater rim was extracted, and this was studied in detail in the forth coming sections. Vegetation is one of the major hindrances in this study, which cannot be eliminated either from the image or from the crater itself. Instead, the effects were minimized by choosing a dry-season image as chosen in this study. The average height of the vegetation in the Lonar crater was assumed as ~5 m and this vegetation error has not caused much difference while performing the topographical analysis.

Results

Lonar Crater Slope

Weathering, erosion and degradation will prominently occur on crater walls (inner and outer), because of their slopes. Lonar crater, whose age is ~50,000 years (GSI 1993) has undergone changes allover the crater and especially along its walls. The erosion is severe along the NE region, which may be due to weathering

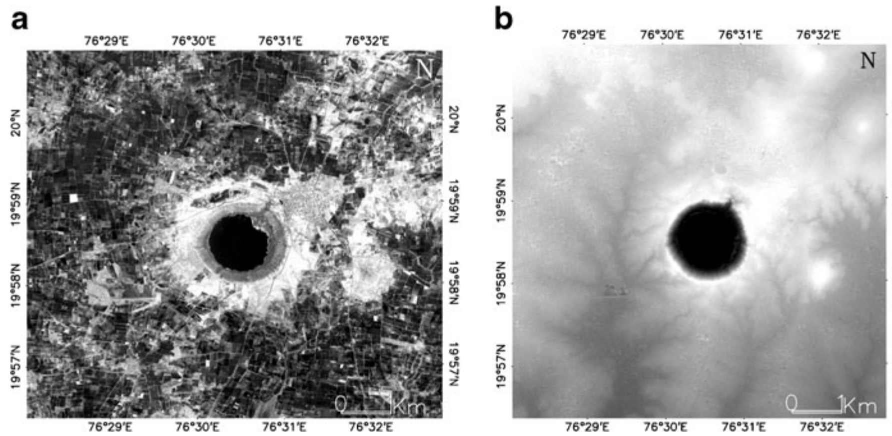

Fig. 1 **a** Cartosat-1 PAN image of Lonar crater and **b** the corresponding DEM

and degradation in the fault along the Dhar canyon (Louzada et al. 2008). Slope asymmetry is a common phenomenon, and this asymmetry may be started during its formation itself and varies over time. The lake at the bottom of the crater poses a difficulty in mapping the slope. To overcome it the lake region was masked to a slope of zero degree before analysis. Figure 2a depicts the density-sliced slope map and Fig. 2b depicts the 3D image and the overall crater topography. Density slicing is an image processing technique that classifies or group the pixel according to the given ranges. It was observed that the slope was non-uniform throughout the crater and reaches a maximum of 80 ° in the north.

The inward slope was calculated from the rim to the bottom (upto 475 m, which is considered as the bottom in this study) which ranges from 0 ° to 80 ° respectively. The slope map (Fig. 2a) was obtained at an interval of 20 °. It was observed that the maximum slope occurs in the range from 20 ° to 39 ° in the inner region, which agrees with Osae et al. (2005) slope of 26 °. The slope of the crater is examined in the inner and the outer region, using spatial profiles along North–south and West–east directions are shown in Fig. 3a–b. Figure 3a depicts that the northern region is steeper (tends to 80 °) whereas the southern part has a gentler slope. Moreover, field observations also indicate the above said asymmetry in the inner slopes (Fig. 3c–d).

The outer slope, calculated from the DEM ranges from 1 ° to 19 °, and is comparatively lesser than for the inner part. The outer part of the crater was undergoing severe modification due to human alteration and erosion. The extensive alteration happened over the NE part where the Lonar town was formed. The average outer slope depicted from the current DEM study is ~16 °. However, the geological map by GSI (1993) on Lonar crater depicts that the outer slope is gentler, and it ranges from 2 ° to 6 °. The variation in outer slope between the current study and the one reported by GSI was observed because of the larger study area considered for this study. In the outer region, the northern part shows a near flat surface due to lower slope variation. This near flat surface is also verified by the poor drainage presence in this part (Fig. 1b). The absence of drainage pattern on the N part raises question whether it was man-made or natural one. On looking at the regional scale (Fig. 1b) the N part is almost flat which clearly depicts that there was less alteration by human except in the NE region where the Lonar town was formed. However, the southern part has the maximum outer slopes, which also have the prominent drainage patterns (Figs. 3a and 1b). Thus, the slope study over the Lonar crater region shows that there is an abrupt change in outer slope along the N–S region. There is not much appreciable difference in slope in the east and the west part of the crater. Thus, hereafter this study concentrates only along the N–S region of the crater to bring out the asymmetry along this region.

The Lonar crater shows an abrupt variation in slope near the rim, and thus it is opined to perform further analysis by spatial profile (Fig. 4). In the inner region the steepness on the northern part creates higher slope (~30 ° to ~50 °) whereas the southern part tends to have comparatively gentler slope (~20 ° to 30 °). On north, the inner slope tends to be ~33 ° at several altitudes and this confirms the steepness. Whereas on south side, the slope tends to be decreasing gradually while moving towards the crater floor from ~25 ° (540 m) to ~20 ° (500 m). However, on the outer region of the crater; the

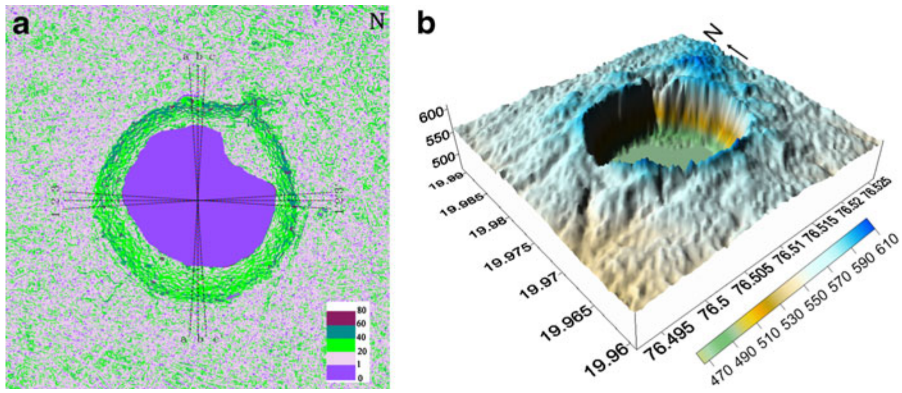

Fig. 2 **a** Density-sliced slope map of the Lonar crater (Transects for spatial profile see Fig. 3). **b** 3D visualization of Lonar crater from Cartosat-1

slope is almost flat out the northern part whereas the slope is abruptly changing on the southern part. The outward slope tends to be ~23 ° near southern part of the rim, which tend to study further on it. Similarly, several studies have been carried on Martian craters about the variation of slopes in the global range (Kreslavsky and Head 2003; Parsons and Nimmo 2009). Such studies concluded that there is asymmetry in the north south slopes of the crater when analysed from equator to poles. Even after exposing to severe alterations Lonar crater still preserves the rim crest on the southern part with the asymmetry. The reason for this is well understood when it is studied regionally, as reported in the next section.

Regional Topographical Analysis and Rim-Uplift in Lonar Crater

Rim uplift is one of the processes that occur during the impact crater formation. Finally formed rim will be a raised one, and this discriminates crater against from the surrounding terrain. The basic process involved in crater rim uplift is well understood, whereas there is a lot of evidence in the crater which has not been fully explored and that may occur at the margins of transient craters (Kring 2007). Therefore, to understand better the horizon view gives an insight about the topographical changes that happened over the impact crater region. The rim uplift will depends on the hardness

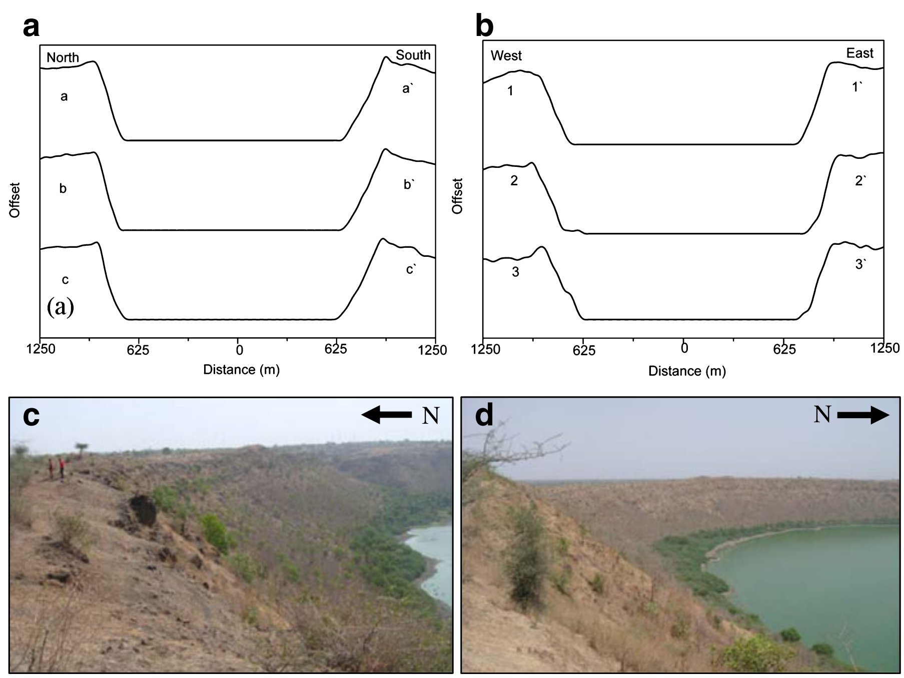

Fig. 3 Spatial profiles of Lonar crater **a** North–south crater profile. **b** West–east profile (respective profiles are plotted over Fig. 2a). **c** Field photo showing northern region of the crater whose slopes are steeper. **d** Field photo of southern region which shows gentle slope

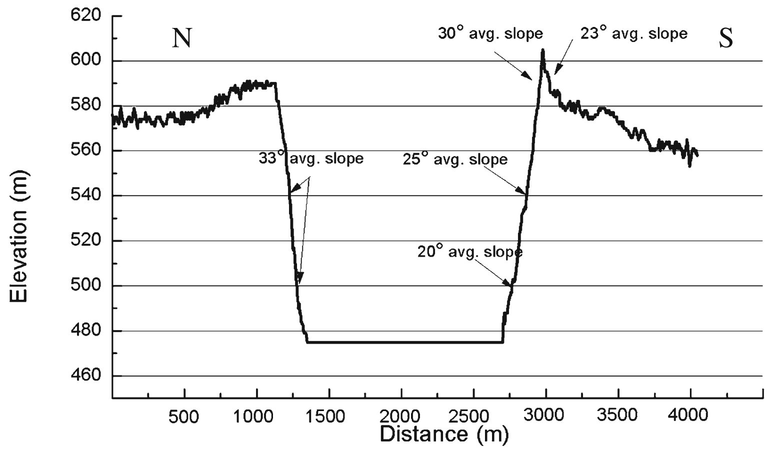

Fig. 4 NS profile showing variation in the rim crest height and also in the slope. (profile line is on Fig. 2)

of the target material, impact velocity, size of the impact object, etc. Meteor crater, rim uplift studies by Poelchau et al. (2009) and Kring (2007) has revealed much about the rim alteration happened on them. On this study, Lonar crater and its surrounding area (region around ~4 crater radii from the centre) has considered for the impact related regional topography changes. The outer region of the crater was frequently undergoing alteration by the human activities. But such activities are overcome by studying on regional basis, because those changes are relatively smaller over a regional area.

The advantage of regional topographical mapping using DEM is to explore any abnormal changes in and around the crater region. Figure 5a shows an insight about the Lonar crater and its surrounding topography (including the Durga hill and the Lonar town). The regional view (Fig. 5a) discloses that the region is undulating in nature, and the terrain tends to descend from north to south with an elevation differences of ~20 m. On observing the crater profile (Fig. 4) and from Fig. 5a, it was decided to concentrate only on the N–S region because of the rim crest abnormality in southern part. The E–W rim was also analyzed but there was not appreciable change. Eastern part is highly human altered and western part is severely eroded (more detail study performed and reported on rim signature chapter).

To find the topographical rise in the rim with respect to the surrounding region, terrain topography profiles were demarcated at equal intervals (~150 m) along N–S direction (Fig. 5b) on both sides of the crater. From these profiles, the average regional profile was computed and compared with the crater profile to analyze the regional rim uplift. We observed that the topographically lower southern rim region is elevated above the average terrain and also higher than the northern part. The northern rim elevated ~10 m to ~15 m whereas the southern rim is ~50 m above the average regional surface (Fig. 5c). From Fig. 5c, it was observed that the pre-impact terrain also descends toward the south. This indicates that the southern part has elevated higher than the northern part, suggesting an inverse relationship between the profile and the regional terrain. From the crater profile, it is observed that the sudden rise in the southern part of the rim is only for a few meters, thereafter it tends to follow the normal terrain (which is descending). This sudden rise in the topography on the southern part clearly indicates the impact effects, which was highlighted because of the regional topographical study carried out using DEM.

The Cartosat DEM data revealed the southern rim uplift abnormality. To justify and evaluate the abnormality, two more dataset were used. They are: Maloof et al. (2010) and SRTM 90 m DEM. Figure 6 shows the results obtained from these two data along with the Cartosat data, which also show that the southern side uplift. We observed that all three dataset show a high correlation and are in agreement with the fact that the terrain is descending (N to S) and the southern rim stands high above the average topography.

The individual spatial profiles extracted on four directions are shown in Fig. 7. The southern profiles reveal the abrupt changes, i.e., from gentle inner slope, steep outward rim with descending terrain. Moreover, the rim uplift is obviously seen in this profile. While the N part shows a steep inner slope and almost a flat surface away from rim. Erosion on the crater rim is not uniform, it is more on the S–SW due to higher slope.

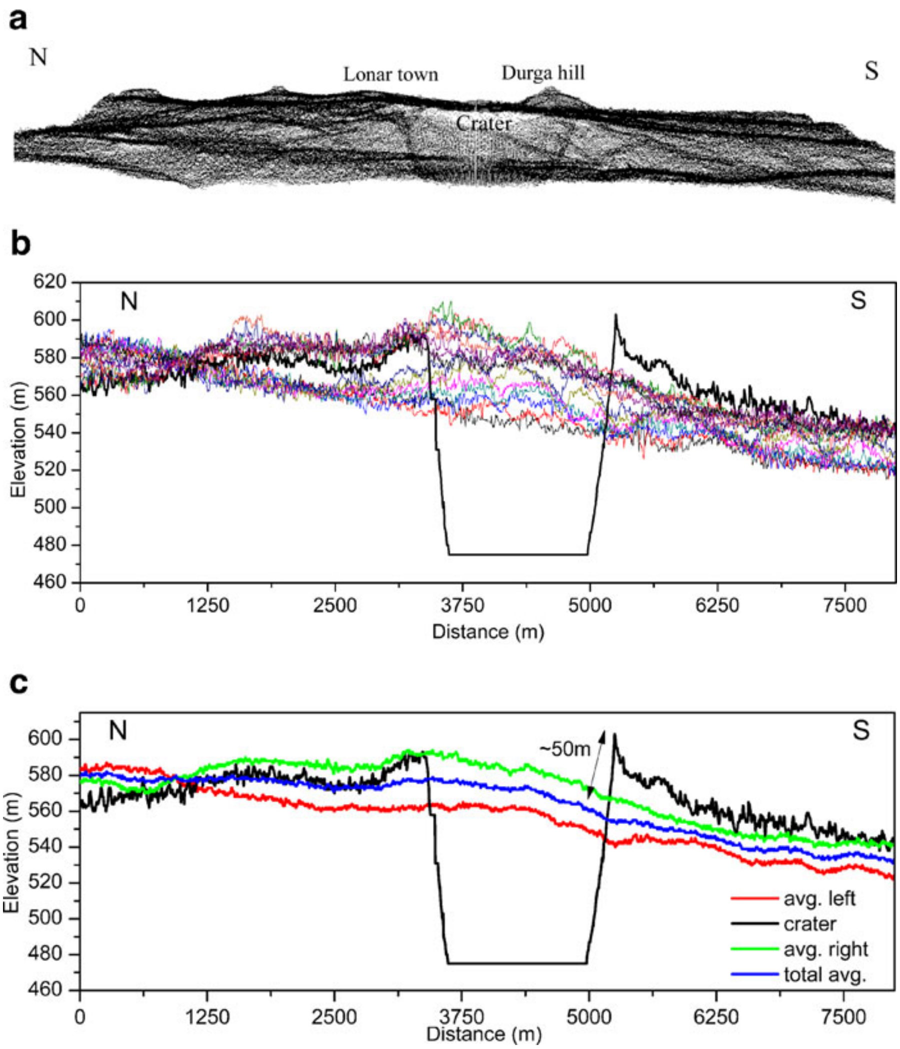

Fig. 5 **a** Topography of the Lonar crater and its surrounding region (horizon view of Fig. 1a), *dashed line* shows the terrain descending along the crater from N to S. **b** Extracted profile along the N–S direction at an interval of 150 m along the N–S in each sides of the crater. All the profile shows a descending surface. **c** Average terrain profile plotted against the crater which shows that the southern part of the rim is elevated ~50 m above the average surface

Whereas, it is comparatively lower on the northern part due to flat surface. From the DEM (Fig. 1b), it was observed that there are more drainage patterns on the S–SW–W side. The presence of more drainage patterns caused due to the descending terrain and moreover, the abnormal uplift along this direction. To verify this topographical change around the Lonar region, the drainage patterns was analyzed around the crater area.

From DEM, it was observed that there are 9 main drainage channels around the crater (NW to E in anti-clockwise). Northern part of the crater shows a small drainage pattern, but not as prominent as on the other parts. The absence is due to the regional near flat surface on the northern part that had prevented the formation of the drainage pattern. The absence of drainage pattern on the NE part (outside crater) is due to severe human alteration. The abnormal uplift along the S–SW part creates prominent drainage pattern and erosion. The southern part is too jagged to form a distinct drainage pattern because of the sudden topographical changes. Due to severe erosion on the western side, the rim is mostly affected and it discussed in next section. Kring (2007) analysed Meteor crater rim uplift and states that, qualitatively a significant fraction of crater rim uplift is attributable to

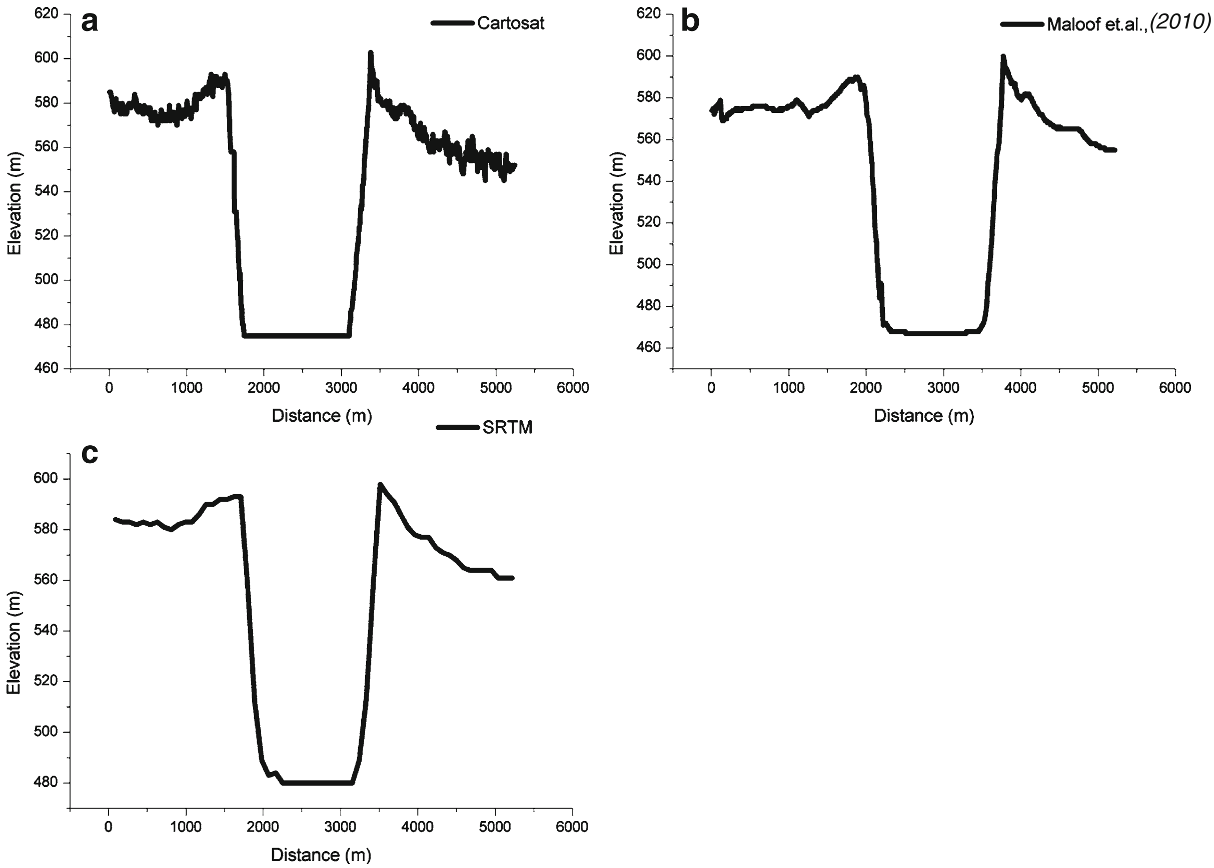

Fig. 6 Crater profile tracked over N–S region (**a**) Cartosat (**b**) Maloof et al. 2010 (**c**) SRTM. All the profiles shows similar southern rim uplift and there after a sudden descending terrain (extracted profile are shown in Fig. 2a)

thrust faults and more work is needed to quantify this contribution. In this case also, it is observed that the

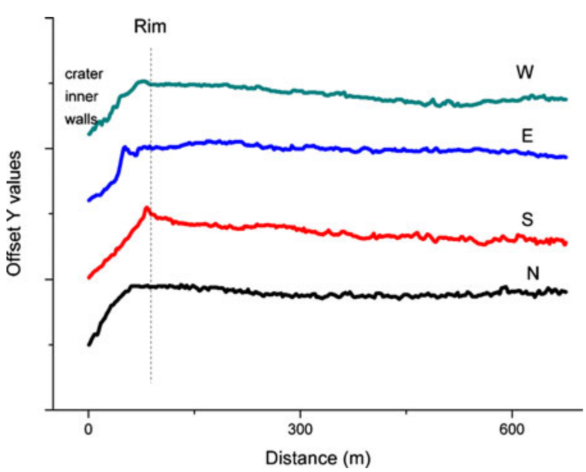

Fig. 7 Profile plot from inner region to outwards along four directions. The inner region gives an insight about the slope in four direction whereas the outer region

DEM study has explored the abnormality in and around the Lonar crater, where further ground truth and analysis may reveal the exact event that caused the abnormality on the southern part. It is obviously from the Fig. 5 that the southern rim uplift is preserved even though it had under gone active erosion. Thus, the Lonar crater opens a new perspective to study impact craters and its effects on a descending terrain.

Lonar Crater Rim Profile/Signature

The study and documentation of the rim topography is an important aspect in analyzing the processes and the effects associated with the impact cratering (Cintala 1979). The raised rim is an outcome of the impact event, this elevated rim stand high above the surrounding terrain. Extraction of the rim from the crater can be easily performed from the DEM. The highest point all over the crater was extracted and these points form the rim of the crater and also act as rim profile/signature.

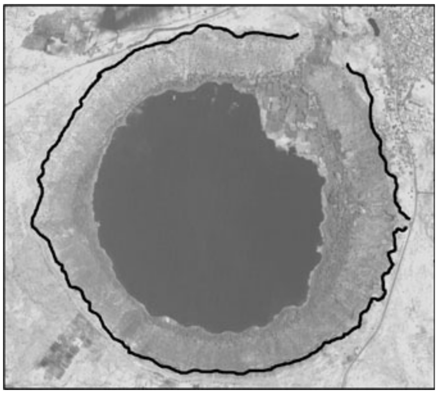

Fig. 8 DEM extracted rim of Lonar crater overlaid on Cartosat-1 PAN image. The NE part of rim is severely eroded. Likewise, the eastern part also shows a similar, but less degraded region

Thus, the rim profile/signature is the plot of the highest points along the crater. Signature profiles used by Bai et al. (2010) for the face recognition shows that, each face profile has a different signature, which will be further useful for the classification of the images. Similarly, the rim signature can act as an identity for crater, which gives the exact boundary and used for further analysis based on the rim.

The DEM extracted rim reveal N–S, E–W and average diameter tends to 1,858 m, 1,870 m and 1,864 m. Figure 8 shows the extracted rim overlaid on the Cartosat-1 Pan image. Moreover, the differences in rim elevation between the highest point of the rim crest in SW at ~614 m and the lowest point in the W at ~575 m, which discloses the jagged nature of the rim. Average rim heights along the four directions are N at ~590 m, E at ~585, S at ~596 m and W at ~578 m. Therefore, the average rim height for the Lonar crater was about ~32 m whereas it was mentioned as ~30 m by Fudali et al. (1980). Similarly, for Meteor crater, rim uplift studies by Poelchau et al.

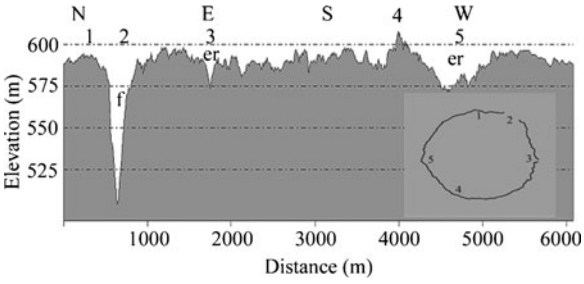

Fig. 9 Rim signature of the Lonar crater with features occurring on the rim (f- fault, er-erosion)

(2009) which indicates that the rim height is about ~50 m. The Lonar crater rim height is relatively lower because of the active erosion and alterations happening over it. From the extracted rim, the circularity index (CI) and rim related events are discussed below.

Circularity index is a parameter which indicates the roundness of a feature. The circularity index for the impact craters is one of the indicators of its maturity, i.e., the circularity decreases with the age of the crater (Adler and Salisbury 1969). The circularity was calculated using; $CI=4\pi*Area/Perimeter^2$. Most of the authors have relied on the 2-dimensional images to compute the CI values. This study, however, utilized the DEM and the extracted rim boundary to compute the CI. It is appropriate to estimate the CI from elevation data rather than the 2D data. The CI for Lonar crater is ~0.902, which indicates it is near-circular in shape and less matured. Lafond and Dietz (1964) and Feldman et al. (1985) are states the same fact that the CI for Lonar crater is higher (i.e., less mature). The CI will be helpful in automatic mapping of craters where these values help in segmenting the crater based on its roundness. Several authors have used this equation to find the roundness of the crater for segmenting the craters (Sawabe et al. 2006; Bandeira et al. 2007; Bue and Stepinski 2007). On the Moon, there are numerous craters, which have been classified based only on their diameters. It is opined that CI may play a role in further differentiating/classifying the craters.

The inner and outer regions of the crater are subjected to severe modification due to mass wasting, erosion, etc. The rim signature for the Lonar crater is hummock in nature. The erosion and degradation event occurring along the rim can be viewed in detail using the rim signature. Figure 9 depicts the features along the rim from the North (1) to the West (5). Location 1: The near flat surface was observed along the N region than any other side. Location 2: The NE region shows the fault effects over the rim. Location 3: The eastern part has an opening in the rim, and this portion is also affected by erosion. Location 4: The SW part holds the highest elevated point in the rim (~614 m). Location 5: The western part holds the best observed V-shaped protrusion caused because of severe erosion, which is also observed during the field visit. Severe erosion has resulted in fewer vegetation covers in this region. Moreover, a similar, but smaller degraded one is also observed on the eastern part. The tip of the V-shaped protrusion usually point outward in the DEM extracted signature because, the inner side has higher slope and severe erosion over this side.

The interior erosion/slumping of materials breach the rim and thereby leading to further crater infilling. Incise rim is along the crater indicates that the crater is altering. This V-shaped protrusion alters not only the rim, but also increase the diameter of the crater. This is a clear indicator of crater degradation state, which was reveled by the DEM based study.

Conclusion

This study has highlighted the need of high resolution DEM for topographical analysis of the crater for better exploration on regional scale. The circularity index derived from the three-dimensional data (DEM) is more accurate than those derived from conventional two-dimensional data. The role of DEM based regional study has precisely brought out the differential topographical uplift. The southern region elevated at ~604 m, which is much above the average elevation (~555 m) of that region. The rim uplift is throughout the crater as a usual event, but the prominent changes had happened over the southern part of the crater. Our observations based on the regional topographical analysis of the crater suggest abnormality on the southern rim-uplift which was also confirmed using Maloof et al. (2010) and SRTM DEM data. Moreover, till now most of the crater studies have concentrated on the crater alone, and not mostly on their surrounding/regional topography. This, regional topographic study has revealed that the Lonar crater was formed on a descending terrain, thus, opening a new perspective in the crater study and emphasizing the importance of surrounding topography also. Further, study is required in this regard to reveal the uplift over the southern part. The southern part of the crater is the prominent zone for geologists to study more about the rim upturn because of the elevated rim and prominent change over in topography. Moreover, the geomorphic process of erosion along the rim in the Lonar crater has been established by identifying the V-shaped protrusions on the rim signature. This alteration on the rim also alters the diameter of the crater thus the average W–E diameter is larger than the average N–S diameter. This study had revealed the importance of regional topography analysis using DEM to understand the crater indeed. It also highlights the differential uplifts in the crater, which is otherwise impossible just only by field study. Thus, the potential role of satellite derived DEM on terrestrial craters will lead to better understanding of planetary craters with more planetary DTM data in the pipeline (TMC of Chandrayaan-1, TC of Selene, etc.,).

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