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Original Article

Litho-structural control of Ambar crater in Deccan Trap, India

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Abstract

The morphology and preservation of impact craters are strongly influenced by the mechanical properties and structural architecture of the target rocks. This study examines the litho-structural control on the morphology of the Ambar impact crater formed within the Deccan Trap basalts of Maharashtra, India. Multi-source remote sensing data, including satellite imagery were integrated with GIS-based morphometric analysis and detailed field investigations to characterize lithological variations, structural elements, and crater geometry. Morphometric parameters such as crater diameter, rim height, wall slope, curvature, and circularity index were quantitatively evaluated and correlated with mapped basalt flow units and fracture networks. The results reveal pronounced spatial variations in rim morphology and slope stability that coincide with flow contacts, joint density, and lineament orientations. Zones of enhanced erosion and rim degradation preferentially follow pre-impact structural weaknesses rather than impact-generated features alone. These observations indicate that lithological heterogeneity and inherited structural fabric exert a first-order control on the post-impact modification and present-day morphology of the Ambar crater. The study highlights the necessity of integrating litho-structural frameworks into impact crater analyses, particularly in layered volcanic terrains.

Keywords: *Ambar impact crater, Deccan Trap basalts, Litho-structural control, Crater morphometry, Lineament analysis*

Introduction

Impact craters are among the most distinctive geomorphic features on planetary surfaces ar and structural framework of the target rocks (Melosh, 1989; French, 1998). Variations in lithology, layering, fracture density, and pre-existing structural discontinuities can significantly modify crater geometry, rim stability, and degradation patterns during post-impact evolution (Pike, 1980; Osinski and Pierazzo, 2013).

Basaltic terrains represent mechanically heterogeneous targets due to the presence of multiple lava flow units, vesicular and amygdaloidal zones, flow contacts, cooling joints, and tectonically inherited fractures. Impact craters developed in such layered volcanic sequences often deviate from idealized circular morphologies predicted by experimental and numerical models based on homogeneous targets (Grieve et al., 1981; Kumar, 2005). Consequently, understanding litho-structural controls on crater morphology is critical not only for terrestrial impact structures but also for interpreting craters on basalt-dominated planetary surfaces such as the Moon and Mars (Head et al., 2010).

The Deccan Traps of peninsular India constitute one of the world's largest continental flood basalt provinces and provide a unique geological setting for investigating impact cratering in layered basaltic substrates. Several impact structures have been reported within or adjacent to the Deccan volcanic province, among which the Lonar crater has received considerable scientific attention (Fredriksson et al., 1973; Maloof et al., 2010). However, other impact structures within the Deccan Traps remain comparatively understudied, particularly with respect to the role of lithological heterogeneity and structural inheritance in controlling crater morphology and degradation.

The Ambar impact crater, developed within Deccan Trap basalts of Maharashtra, India, represents an important but relatively less explored terrestrial impact structure. Preliminary studies have focused mainly on its identification and general morphology, while detailed investigations linking crater geometry with lithological variability and structural architecture are lacking.

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In particular, the influence of basalt flow boundaries, joint systems, and lineament patterns on rim asymmetry, wall slope variation, and erosion intensity has not been quantitatively assessed.

Advances in remote sensing, digital elevation models (DEMs), and GIS-based morphometric techniques now enable high-resolution analysis of crater morphology and its relationship with litho-structural parameters (Pike et al., 2009; Chandnani et al., 2019). When integrated with field-based geological and structural observations, these approaches provide robust frameworks for evaluating post-impact modification processes and identifying the controls exerted by target rock properties.[1]

In this study, I have examined the litho-structural control on the morphology of the Ambar impact crater using an integrated approach that combines multi-source satellite data, DEM-derived morphometric analysis, GIS-based spatial correlation, and detailed field investigations. By quantitatively relating crater morphometric parameters—such as diameter, rim height, wall slope, curvature, and circularity—with mapped basalt flow units and fracture networks, this study aims to elucidate the role of inherited lithological and structural heterogeneity in shaping the present-day morphology of the crater. The findings contribute to a broader understanding of impact crater evolution in layered volcanic terrains and offer valuable implications for terrestrial and planetary impact studies.

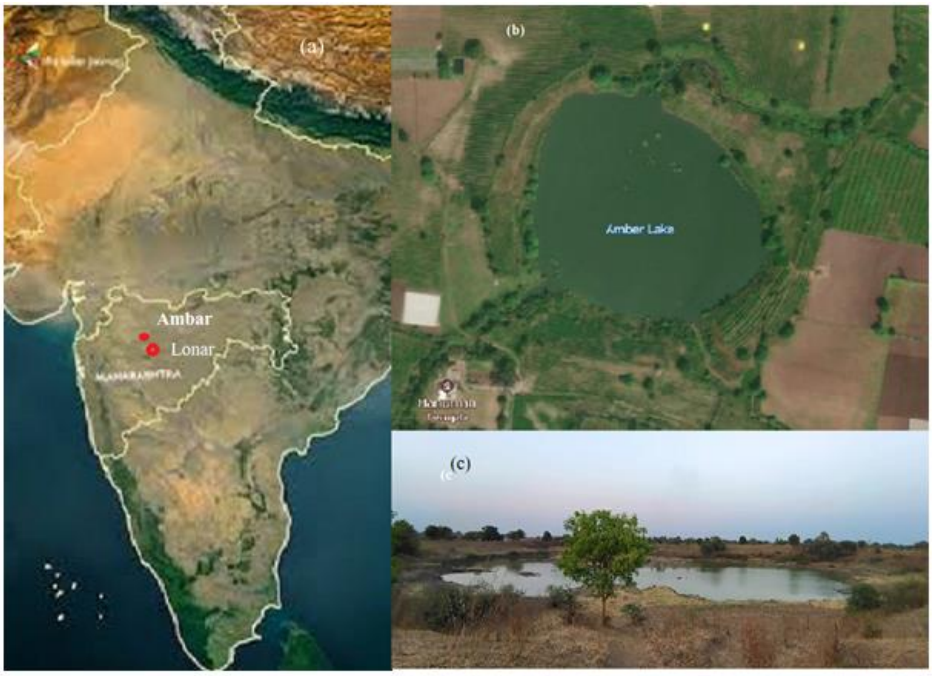

Fig.1 Location Map of the Ambar crater (a) Location of Ambar in Maharashtra, India (b) Google image of the Ambar crater (c) Panoramic view of the Ambar crater

Study Area

The Ambar impact crater is situated in Buldhana District, eastern Maharashtra, India, within the central part of the Deccan Trap Large Igneous Province. The crater lies in close proximity to Lonar town, approximately 85 km southwest of Akola and 150 km east of Aurangabad, and is located between 19°58′ and 20°00′ N latitude and 76°29′ and 76°32′ E longitude (Fig. 1). The study area forms part of the north-central Deccan volcanic plateau, a region characterized by extensive basaltic lava flows of Late Cretaceous to Early Paleogene age.Physiographically, the Ambar crater occurs on a gently undulating plateau surface at an average elevation of ~500–550 m above mean sea level. The regional topography is dominated by flat-topped interfluves and shallow valleys developed through prolonged fluvial erosion of the basaltic terrain. The crater structure is morphologically expressed as a circular to sub-circular depression with a well-defined rim, standing out distinctly from the surrounding plateau surface.

Geologically, the crater is excavated entirely within layered Deccan Trap basalts, which consist of multiple lava flow units separated by flow contacts and weathered horizons. These basalt flows display marked lithological heterogeneity, including massive basalt cores, vesicular and amygdaloidal flow tops, and red bole layers. The basaltic sequence is pervasively affected by cooling joints, columnar jointing, tectonic fractures, and regional lineaments, which impart strong mechanical anisotropy to the target rocks. Such inherited litho-structural characteristics play a crucial role in governing crater morphology, rim stability, and post-impact erosional modification.[2]

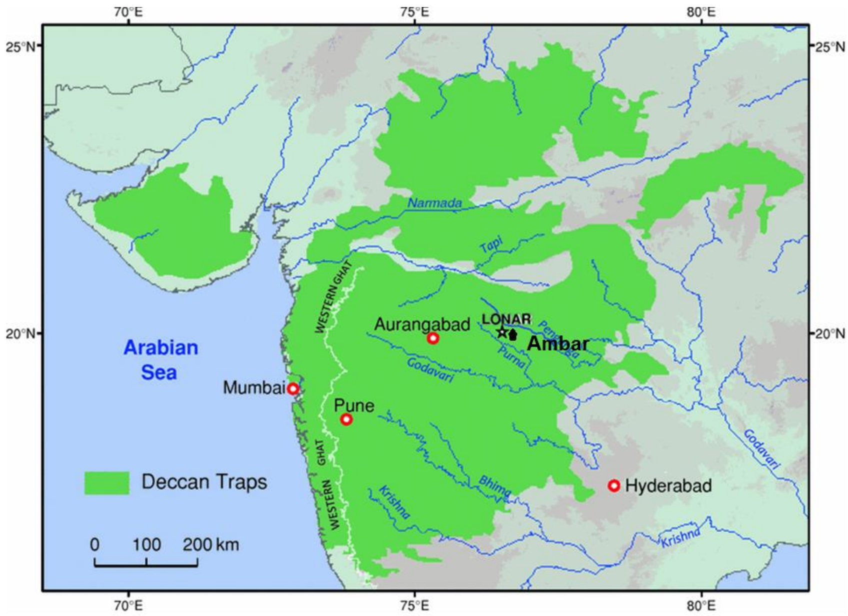

Fig. 2.Location of Ambar crater on Deccan Traps

Structurally, the region is influenced by regional ENE–WSW, NE–SW, and NW–SE trending lineaments, commonly observed across the Deccan Traps and interpreted as expressions of tectonic fractures and dyke-related structures. These structural elements intersect the crater rim and walls, providing pathways for preferential erosion, slope instability, and drainage development.

Climatically, the Ambar crater region experiences a semi-arid to sub-humid tropical monsoonal climate, with mean annual rainfall ranging between 700 and 900 mm, most of which occurs during the southwest monsoon (June–September). Seasonal rainfall and associated surface runoff significantly influence weathering, mass wasting, and sediment redistribution along the crater walls and floor, thereby contributing to the progressive degradation of crater morphology.[3]

The combination of well-preserved impact morphology, layered basaltic lithology, and strong structural fabric makes the Ambar impact crater an ideal natural laboratory for investigating litho-structural controls on impact crater morphology and post-impact landscape evolution in volcanic terrains. Moreover, its location within the Deccan Traps provides important analogs for interpreting impact craters developed in basalt-dominated planetary surfaces such as the Moon and Mars.[4,5]

Data and Methods

1. Data Sources

To investigate the litho-structural control on the morphology of the Ambar impact crater, an integrated dataset comprising remote sensing imagery, geological maps, and field observations was employed.

1. Remote Sensing Data

Multi-source satellite data were used to characterize surface morphology, lithological variation, and structural features:

- Sentinel-2 MSI imagery (10 m spatial resolution) for lithological discrimination, surface texture analysis, and lineament mapping.
- Landsat-8/9 OLI data (30 m resolution) for regional geomorphic context and multi-band spectral analysis.
- High-resolution Google Earth imagery for visual interpretation, validation of lineaments, and mapping of small-scale geomorphic features.

2. Geological and Structural Data

- Geological Survey of India (GSI) maps (1:50,000 scale) were used as baseline lithological references.
- Field-based lithological and structural measurements were collected to validate remote sensing interpretations.

2. Remote Sensing and GIS Processing

All spatial datasets were processed and analyzed using ArcGIS/QGIS and standard remote sensing software.

1. Lithological Mapping

Lithological units within and around the crater were delineated using:

- False-color composites and band ratios to enhance basalt flow textures.
- Visual interpretation of surface roughness, weathering patterns, and tonal contrasts corresponding to massive basalt cores, vesicular/amygdaloidal flow tops, and flow contacts.
- Field verification of interpreted lithological boundaries.

2. Structural and Lineament Analysis

Structural features were mapped using a combination of:

- Manual lineament extraction from satellite imagery and shaded-relief DEMs.
- Automatic lineament detection from hillshade images generated under multiple illumination angles.

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- Orientation analysis of lineaments using rose diagrams to identify dominant structural trends.

Lineament density maps were generated to quantify spatial variations in fracture intensity across the crater.

3. DEM-Based Morphometric Analysis

Crater morphometry was quantified using DEM-derived parameters to evaluate variations in crater geometry and preservation state.

The following morphometric parameters were extracted:

- Crater diameter
- Rim height
- Crater depth
- Wall slope angle
- Profile and plan curvature
- Surface roughness
- Circularity index and asymmetry ratio

Slope, curvature, and roughness maps were derived using standard terrain analysis algorithms. Radial and azimuthal profiles were generated across the crater to assess rim symmetry and wall steepness variations.[6]

4. Litho-Structural Correlation Analysis

To assess litho-structural control on crater morphology:

- Morphometric layers were spatially overlaid with lithological maps and lineament density maps.
- Statistical correlations were examined between rim height, slope angle, and erosion intensity versus basalt flow boundaries and fracture density.
- Zones of enhanced degradation were evaluated with respect to pre-impact structural fabric rather than impact-generated features alone.

5. Field Investigations

Field surveys were conducted to validate remote sensing and GIS interpretations and to document litho-structural characteristics.

Field observations included:

- Identification of basalt flow units and flow contacts.
- Measurement of joint orientations, fracture spacing, and fault traces using a geological compass.
- Documentation of weathering patterns, mass wasting features, and erosion along crater walls and rim.

Structural data collected in the field were integrated with GIS-based lineament datasets for consistency checks.

6. Comparative and Conceptual Analysis

The morphometric and litho-structural characteristics of the Ambar crater were compared with:

- Idealized simple impact crater models in homogeneous targets.
- Published morphometric data from the Lonar impact crater.

Based on the integrated results, a conceptual litho-structural model was developed to explain the role of basalt flow heterogeneity and inherited structural weaknesses in controlling crater morphology and post-impact modification.

Methods

An integrated methodological approach combining remote sensing analysis, GIS-based morphometry, structural mapping, and field validation was adopted to evaluate the litho-structural control on the morphology of the Ambar impact crater developed within Deccan Trap basalts.

- **Remote Sensing and GIS Analysis**

Multi-spectral satellite imagery was processed to enhance lithological contrasts and identify surface textures and structural features. False-colour composites and band ratio techniques were applied to discriminate basalt flow units based on spectral response, surface roughness, and weathering characteristics. Lineaments were extracted using a combination of visual interpretation of satellite imagery and shaded-relief DEMs generated under multiple illumination angles to minimize directional bias.

All spatial datasets were georeferenced to a common coordinate system and analyzed within a GIS environment. Lineament orientation data were statistically analyzed using rose diagrams to determine dominant structural trends, while lineament density maps were generated to quantify spatial variations in fracture intensity.

- **DEM-Based Morphometric Analysis**

Crater morphology was quantified using digital elevation models through standard terrain analysis techniques. Morphometric parameters including crater diameter, rim height, crater depth, wall slope angle, profile and plan curvature, surface roughness, circularity index, and asymmetry ratio were derived. Slope, curvature, and roughness maps were generated to evaluate spatial variability in crater wall steepness and degradation. Radial and azimuthal topographic profiles were extracted to assess rim symmetry and identify zones of differential erosion.[7]

- **Litho-Structural Correlation**

Morphometric parameters were spatially overlaid with lithological boundaries and lineament density maps to evaluate the influence of lithology and structural fabric on crater morphology. Statistical comparisons were performed to examine relationships between rim height, wall slope, and erosion intensity and the distribution of basalt flow contacts and fracture density. Areas of enhanced degradation were interpreted in relation to inherited structural weaknesses rather than impact-generated features alone.

- **Field Validation**

Field investigations were carried out to validate interpretations derived from remote sensing and GIS analyses. Lithological units and flow contacts were identified, and structural elements such as joints, fractures, and faults were measured using a geological compass. Observations of weathering patterns, mass-wasting processes, and erosional features along crater walls and rim were documented and integrated with spatial datasets.

Field validation of the Ambar crater was carried out through systematic ground surveys to verify interpretations derived from remote sensing and GIS analyses. Radial and circumferential traverses around the

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crater rim and inner walls confirmed the presence of multiple Deccan Trap basalt flow units, including massive and vesicular–amygdaloidal basalts, as well as distinct flow contact zones. Structural measurements recorded in the field show dominant NE–SW and NW–SE joint and fracture orientations, which closely correspond with lineament patterns mapped from satellite imagery and DEM hillshade analysis.[8] Areas of high fracture density and flow contacts observed in the field coincide with sectors of reduced rim height, gentler slopes, and enhanced erosion identified in morphometric maps. Overall, field observations provide strong ground-truth support for the inference that lithological heterogeneity and inherited structural fabric exert a primary control on the present-day morphology and degradation of the Ambar impact crater.

- **Comparative and Conceptual Interpretation**

The morphometric and litho-structural characteristics of the Ambar crater were compared with idealized simple impact crater models and published data from the Lonar impact crater. Based on the integrated analyses, a conceptual model was developed to illustrate the role of basalt flow heterogeneity and inherited structural fabric in controlling crater morphology and post-impact modification.

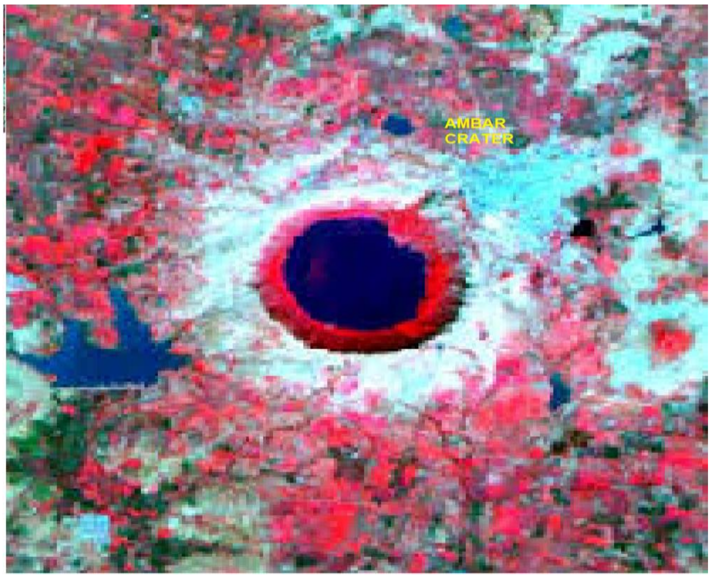

Fig.2. IRS-LISS-III image of Ambar, Lonar crater,India

Result

1. Lithological Distribution

Lithological mapping of the Ambar impact crater reveals that the structure is developed entirely within layered Deccan Trap basalts. Distinct basalt flow units were identified based on spectral characteristics, surface texture, and field verification. Massive basalt cores dominate the crater rim and upper wall sections, whereas vesicular and amygdaloidal basalts are more prevalent along flow tops and at specific segments of the crater wall. Flow contacts and weathered horizons are discontinuously exposed along the crater rim and inner slopes, indicating significant lithological heterogeneity within the target rocks.[9]

The spatial distribution of these lithological units shows an uneven pattern around the crater perimeter, with certain rim segments coinciding with mechanically weaker flow tops and altered basalt zones.

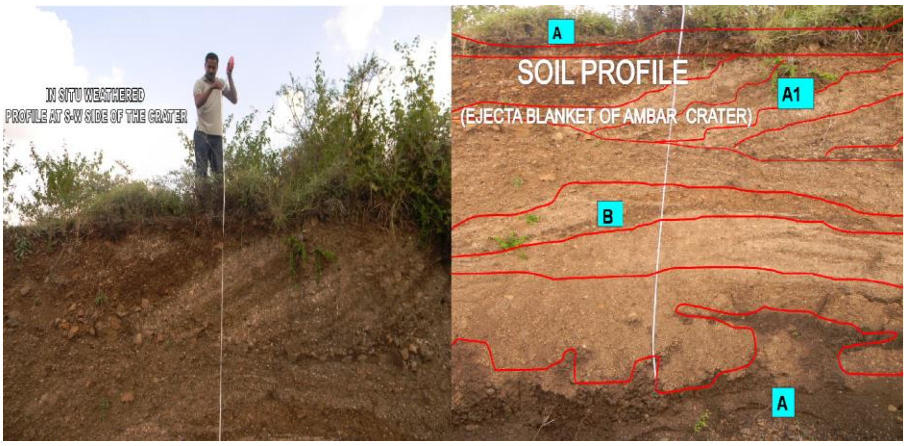

Fig.3. Measurement of Lithological sections of the Ambar Crater

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Table 1. Lithological Units Identified in the Ambar Crater

Unit ID	Lithology	Field Characteristics	Mechanical Behavior
B1	Massive basalt	Dense, columnar joints	High strength
B2	Vesicular basalt	Vesicles, weathered	Moderate strength
B3	Amygdaloidal basalt	Mineral-filled vesicles	Variable strength
B4	Flow contact zones	Fractured, altered	Low strength

Structural and Lineament Characteristics

Structural mapping identified a well-developed network of fractures, joints, and Lineaments within and around the Ambar crater. Lineament analysis indicates the dominance of NE–SW, ENE–WSW, and NW–SE trending structural orientations, consistent with regional tectonic trends of the Deccan Trap province. Rose diagram analysis demonstrates that these orientations are persistent across both the crater interior and the surrounding plateau.[10,11,12]

Lineament density mapping reveals spatial variability in fracture intensity, with higher densities observed along specific crater rim segments and inner walls. These high-density zones frequently coincide with mapped basalt flow contacts and areas of enhanced surface dissection.

Crater Morphometry

DEM-based morphometric analysis shows that the Ambar crater exhibits a sub-circular geometry with measurable deviations from ideal circularity. The crater diameter and rim height vary azimuthally, indicating asymmetric crater morphology. Rim elevation profiles demonstrate pronounced variations, with certain rim sectors exhibiting reduced height and gentler slopes compared to others.[13,14,15]

Wall slope analysis reveals steep slopes along segments underlain by massive basalt units, whereas gentler slopes and irregular profiles characterize areas associated with vesicular basalts and high fracture density. Curvature maps indicate alternating zones of concave and convex surfaces along the crater walls, reflecting differential erosion patterns.Surface roughness values are elevated along structurally controlled zones and areas affected by mass wasting, while smoother surfaces dominate relatively stable rim segments.

Circularity and Asymmetry Patterns

The calculated circularity index indicates that the crater deviates from a perfectly circular form, with elongation observable along specific structural orientations. The asymmetry ratio derived from radial profiles highlights systematic differences in rim height and wall steepness between opposing crater sectors.
Azimuthal analysis of morphometric parameters shows that sectors aligned with dominant lineament orientations correspond to reduced rim height, increased wall degradation, and enhanced erosion signatures.[15]

Litho-Structural Control on Morphology

Spatial overlay analysis demonstrates a strong correspondence between morphometric variability and litho-structural features. Zones of reduced rim height, gentler wall slopes, and increased surface roughness coincide with areas of high fracture density and basalt flow contacts. In contrast, crater segments developed in massive, less fractured basalt units display relatively steeper slopes and better-preserved rim morphology.[16]

Areas of enhanced erosion and rim degradation preferentially align with pre-existing structural weaknesses rather than being uniformly distributed around the crater. These patterns indicate that inherited lithological and structural heterogeneity exerts a measurable influence on present-day crater morphology.

Table,2, GPS Survey Data of the Ambar Crater

Point ID	Feature Type	Latitude (N)	Longitude (E)	Elevation (m amsl)	Lithology	Structural Notes
G1	Rim crest	19°59′12″	76°30′18″	—	Massive basalt	Low fracture density
G2	Rim crest (degraded)	19°59′05″	76°30′42″	—	Vesicular basalt	High joint density
G3	Inner wall (upper)	19°58′54″	76°30′25″	—	Flow contact zone	Fracture-controlled erosion
G4	Inner wall (lower)	19°58′47″	76°30′30″	—	Vesicular basalt	Rock fall observed
G5	Crater floor	19°58′40″	76°30′35″	—	Weathered basalt	Surface runoff channels

Field Validation Results

Field observations corroborate remote sensing and DEM-based findings. Fracture spacing and joint density are noticeably higher along degraded rim sectors, while intact rim sections are underlain by comparatively massive basalt. Evidence of weathering, rock fall, and slope instability is concentrated along structurally controlled zones and flow contact exposures.Measured joint orientations obtained during field surveys are consistent with lineament trends extracted from satellite imagery, confirming the reliability of remote sensing-based structural mapping.

Fig.4. Litho-Structural Soil profile inside the Ambar crater

Comparative Results

Comparison with published morphometric data from the Lonar impact crater indicates both similarities and contrasts. While both craters are developed in Deccan Trap basalts, the Ambar crater exhibits greater morphometric asymmetry and more pronounced litho-structural control on rim preservation. Differences in rim continuity, slope stability, and erosion intensity highlight the influence of localized lithological variability and structural fabric.

Fig. 5. Panoramic View of Ambar crater

Discussion

1. **Litho-Structural Control on Crater Morphology**

The results demonstrate that the present-day morphology of the Ambar impact crater is strongly influenced by the lithological heterogeneity and inherited structural fabric of the Deccan Trap basalts. Variations in rim height, wall slope, circularity, and surface roughness show clear spatial correspondence with basalt flow units and fracture density. Crater sectors developed in massive basalt units exhibit comparatively steeper slopes and better-preserved rims, whereas segments associated with vesicular basalts and flow contact zones show enhanced degradation and gentler wall profiles.[18,19,20] These findings indicate that post-impact geomorphic evolution at Ambar has been governed primarily by differential erosion controlled by lithological strength contrasts rather than by impact-related processes alone. Similar litho-structural controls have been reported from other impact structures developed in layered volcanic terrains, emphasizing the role of target rock properties in modifying crater morphology over geological timescales.

2. **Role of Pre-Impact Structural Fabric**

The alignment of rim degradation zones and crater asymmetry with dominant regional lineament orientations suggests that pre-existing structural weaknesses exert a first-order control on post-impact modification. High lineament density zones coincide with reduced rim height and increased erosion intensity, indicating preferential weathering along fracture networks. These observations support the interpretation that inherited tectonic structures guided erosion pathways and slope instability following crater formation.[21,22,23]

The persistence of regional NE–SW and NW–SE structural trends within the crater interior implies that the impact did not completely obliterate the pre-impact structural framework. Instead, the impact overprinted this fabric, which subsequently re-emerged as a controlling factor during post-impact landscape evolution.

3. **Implications for Impact Craters in Layered Volcanic Terrains**

The Ambar crater provides an important analogue for understanding impact craters formed in layered basaltic targets on Earth and other planetary bodies. The observed litho-structural control highlights the need to account for target rock heterogeneity when interpreting crater morphometry, degradation state, and preservation potential. Failure to consider lithological and structural controls may lead to misinterpretation of impact dynamics or crater age based solely on morphological criteria.

Comparative analysis with the Lonar impact crater further illustrates that craters formed within the same volcanic province can exhibit markedly different morphometric characteristics depending on local litho-structural conditions. This underscores the importance of site-specific geological context in impact crater studies.[23,24]

4. **Post-Impact Modification and Landscape Evolution**

The spatial variability in erosion, mass wasting, and rim degradation observed at Ambar indicates that post-impact processes have played a dominant role in shaping the current crater morphology. Climatic conditions, coupled with lithological weakness and fracture-controlled drainage, have facilitated selective erosion along structurally vulnerable zones. Over time, these processes have accentuated crater asymmetry and reduced overall rim continuity.

The integration of morphometric, structural, and field data provides a robust framework for disentangling impact-related features from post-impact geomorphic modification, contributing to a more accurate reconstruction of crater evolution.[25]

Limitations

Despite the comprehensive multi-dataset approach, several limitations should be acknowledged:

1. **DEM Resolution Constraints:** The spatial resolution of available DEMs may not capture micro-scale geomorphic features or subtle deformation structures within the crater.
2. **Subsurface Information Gaps:** The absence of geophysical or borehole data limits insights into subsurface lithological variations and impact-induced deformation.
3. **Temporal Constraints:** Quantitative constraints on the timing and rate of post-impact erosion remain limited, restricting precise chronological reconstruction of crater modification.
4. **Lineament Interpretation Uncertainty:** Some mapped lineaments may reflect erosional or anthropogenic features rather than true tectonic structures, despite field validation efforts.

Future studies integrating high-resolution LiDAR, geophysical surveys, cosmogenic nuclide dating, and numerical modeling would significantly enhance understanding of impact–structure–erosion interactions at Ambar.

Conclusions

This study provides a comprehensive assessment of litho-structural controls on the morphology and preservation of the Ambar impact crater developed within the Deccan Trap basalts of India. The integration of remote sensing, GIS-based morphometric analysis, and field investigations reveals that lithological heterogeneity and inherited structural fabric exert a dominant influence on crater geometry, rim preservation, and post-impact erosion patterns.

Key conclusions are:

1. The Ambar crater exhibits significant morphometric asymmetry and spatial variability in rim height, slope, and circularity.
2. Zones of enhanced erosion and rim degradation correspond closely with basalt flow contacts and high fracture density areas.
3. Pre-impact structural trends have guided post-impact erosion and landscape evolution, overriding impact symmetry.
4. Litho-structural frameworks are essential for accurate interpretation of impact crater morphology in layered volcanic terrains.

The findings contribute to a broader understanding of impact cratering processes in heterogeneous targets and provide valuable insights applicable to terrestrial and planetary impact studies.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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