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Geomorphic Study of Post-Impact Landscape Evolution of the CIE Mesa, Dhala Impact Structure, Madhyapradesh, India

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Abstract

The CIE Mesa within the Dhala impact structure of Madhya Pradesh, India presents a unique opportunity to investigate the long-term geomorphic evolution of an ancient impact site within a cratonic setting. Despite its origin in a Paleoproterozoic meteorite impact, much of the original crater morphology has been obscured by prolonged post-impact erosion and subsequent sedimentary processes. This study integrates field observations, detailed stratigraphic logging, and geomorphic mapping to reconstruct the erosional history of the CIE Mesa and its surrounding landscape. The analysis focuses on the spatial distribution of denudational remnants, Fluvial incision patterns along radial drainage networks, and the relationship between mesa topography and underlying lithologies to understand mechanisms of slope retreat and landscape modification over geological time. Findings reveal that differential weathering and fluvial incision have significantly reworked the crater's original topography, reducing its expression to a subdued basin and isolating the mesa as a resistant geomorphic remnant. These insights enhance our understanding of how ancient impact structures evolve in tectonically stable terrains and provide a framework for comparing erosion signatures among other deeply weathered craters worldwide.

Keywords: *Dhala impact structure, CIE Mesa geomorphology, Post-impact erosion Landscape evolution, Crater denudation, Fluvial incision, Slope retreat*

Introduction

Meteorite impact craters represent unique geological landforms that undergo rapid formation followed by prolonged modification through surface and subsurface processes. While the initial impact produces distinct diagnostic features, the long-term preservation of crater morphology is strongly influenced by post-impact erosion, sedimentation, tectonic stability, and climatic conditions (Melosh, 1989; French and Koeberl, 2010). In ancient cratonic regions, such as the Indian shield, many impact structures have been deeply eroded, leaving behind only subdued geomorphic expressions that require integrated field-based investigation for their recognition and interpretation (Grieve et al., 2008).

The Dhala impact structure, located in the Shivpuri district of Madhya Pradesh, India, is one of the oldest confirmed terrestrial impact craters, with an estimated Paleoproterozoic age of ~2.5 Ga (Pati et al., 2010; Joshi et al., 2023). The structure is developed within the Bundelkhand granitoid complex and partially overlain by sedimentary sequences of the Vindhyan Supergroup. Unlike younger and well-preserved impact craters, the original morphology of the Dhala crater has been substantially altered due to prolonged denudational processes, making it an ideal natural laboratory for studying post-impact landscape evolution in a tectonically stable continental interior (Pati et al., 2019).

One of the most prominent geomorphic features within the Dhala impact structure is the Central Inner Elevated (CIE) Mesa, which rises conspicuously above the surrounding terrain. The mesa is composed predominantly of sedimentary rocks resting on impact-modified basement, and its preservation is attributed to differential erosion controlled by lithological resistance and structural configuration (Agarwal et al., 2020). Previous studies have focused largely on impact diagnostics such as shock metamorphic features, breccias, and melt rocks (Pati et al., 2010; French et al., 2017), whereas the geomorphic evolution of the CIE Mesa and its role in understanding crater degradation has received comparatively limited attention.

Post-impact erosion plays a crucial role in transforming fresh impact craters into subdued landforms, often resulting in the selective preservation of resistant units as mesas, buttes, or residual hills (Hergarten and Kenkmann, 2015; Kenkmann et al., 2014). Processes such as fluvial incision, slope retreat, weathering, and sediment reworking progressively reduce crater relief and obscure primary impact features.

In the case of Dhala, regional drainage reorganization and long-term denudation under tropical to semi-arid climatic regimes have significantly modified the crater landscape, isolating the CIE Mesa as a key remnant of the original post-impact stratigraphy (Singh et al., 2021).

Understanding the post-impact erosion and landscape evolution of the CIE Mesa is therefore essential for reconstructing the geomorphic history of the Dhala impact structure. Such an approach not only provides insights into the degradation pathways of ancient impact craters but also contributes to broader discussions on the preservation potential of impact-induced landforms in Precambrian terrains. This study aims to analyze the geomorphic evolution of the CIE Mesa through field-based observations and landscape analysis, emphasizing the role of erosional processes in shaping one of the oldest known impact structures on Earth.[1]

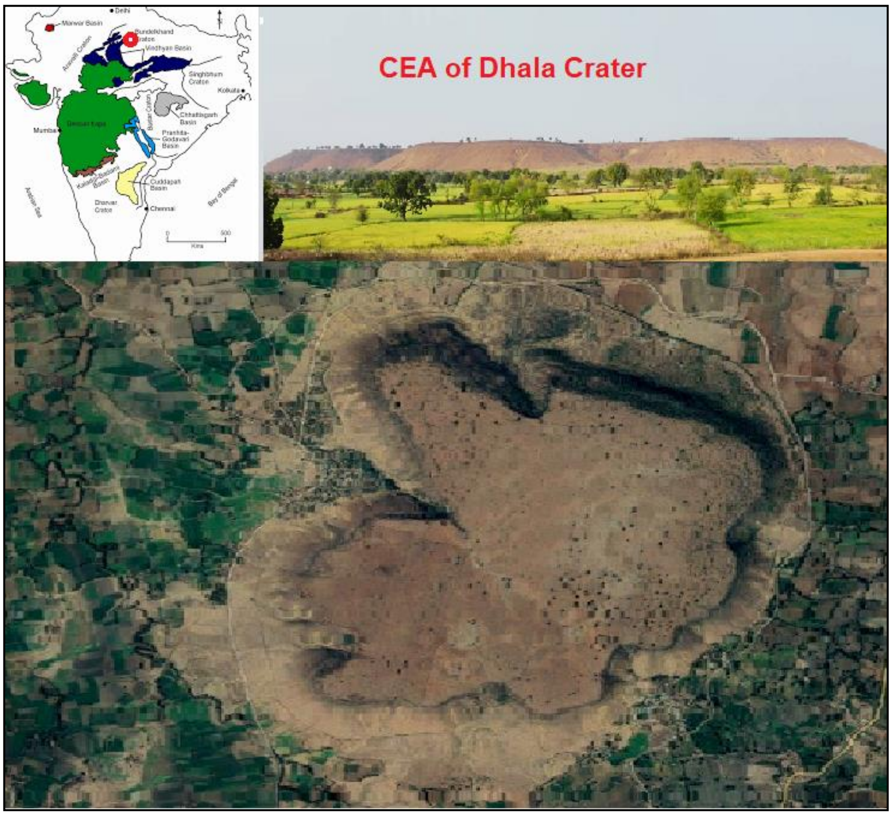

Fig.1. Location map of Dhala Crater (a) Geology Map (b) Panoramic View of Dhala crater rim (c) Google Earth Image of Dhala Crater 2024

Study Area

The present study focuses on the Central Inner Elevated (CIE) Mesa located within the Dhala impact structure in the Shivpuri district of Madhya Pradesh, central India. The Dhala impact structure is situated on the northern part of the Bundelkhand craton and represents one of the oldest known terrestrial impact sites. Geographically, the study area lies between approximately 25°18′ N to 25°22′ N latitude and 78°05′ E to 78°10′ E longitude, covering the central portion of the impact structure including the CIE Mesa and its immediate surroundings.

The Dhala impact structure occurs within granitoid rocks of the Bundelkhand complex and is partially overlain by sedimentary formations of the Vindhyan Supergroup. The CIE Mesa forms a prominent elevated landform rising above the surrounding undulating terrain, with relatively steep flanks and a comparatively flat summit surface. The elevation contrast between the mesa top and adjacent plains highlights the role of differential erosion and lithological control in shaping the present-day landscape.

Climatically, the region experiences a semi-arid to sub-humid tropical monsoon climate, characterized by seasonal rainfall concentrated during the southwest monsoon and prolonged dry periods. These climatic conditions, combined with long-term tectonic stability, have favored extensive weathering, fluvial incision, and surface denudation over geological timescales. Drainage in and around the study area is dominated by ephemeral to seasonal streams that exhibit structurally and lithologically controlled patterns, contributing to progressive erosion of the impact-modified terrain.[2]

The relative accessibility of the CIE Mesa and the presence of well-exposed lithological contacts make the area particularly suitable for detailed field-based geomorphological investigations. The defined spatial extent allows focused analysis of post-impact erosional processes and landscape evolution within the central domain of the Dhala impact structure.

Data and Methods

1. **Data Sources**

The present study is based primarily on field-derived geomorphological data supported by topographic and satellite datasets. Field data include direct observations of landforms, lithological contacts, erosional surfaces, slope characteristics, drainage features, and weathering profiles across the CIE Mesa and its surrounding terrain. Detailed field mapping was carried out to document geomorphic units, relative relief, slope morphology, and evidence of post-impact denudational processes.

Secondary datasets include Survey of India (SOI) topographic maps (1:50,000 scale) used for elevation reference, drainage analysis, and base map preparation. Freely available satellite imagery (e.g., multispectral and high-resolution optical data) was utilized to identify surface expressions of geomorphic features, drainage patterns, and spatial relationships between the mesa and adjacent landscape units. Digital Elevation Models (DEMs) were employed to extract elevation profiles, slope gradients, and relative relief across the study area.

2. **Field Methods**

Systematic field surveys were conducted across the CIE Mesa, its flanks, and the surrounding plains to document geomorphic features related to post-impact erosion. Traverses were planned along radial and circumferential directions relative to the mesa to capture spatial variations in landform development. Key observations included mesa edge morphology, slope angles, evidence of scarp retreat, weathering intensity, and nature of erosional contacts between lithological units.

Lithostratigraphic observations focused on identifying resistant and less resistant rock units contributing to differential erosion. Measurements of joint spacing, fracture density, and orientation were recorded where exposed, as these structural elements influence weathering and fluvial incision. Field photographs, GPS-based location points, and descriptive logs were used to systematically document geomorphic and geological features.

3. **Geomorphological Analysis**

Geomorphological mapping was carried out by integrating field observations with satellite imagery and topographic data. Landforms such as mesas, pediments, valleys, and erosional remnants were delineated to understand spatial patterns of denudation. Drainage characteristics, including stream order, pattern, and incision style, were analyzed to assess the role of fluvial processes in post-impact landscape modification.[3]

Topographic profiles were generated across the mesa and surrounding areas to evaluate relative relief and slope asymmetry. These profiles aided in interpreting erosion intensity, slope retreat mechanisms, and the degree of landscape lowering since the impact event. Particular emphasis was placed on identifying geomorphic indicators of long-term stability versus active erosion.

4. **Interpretative Approach**

The evolution of the CIE Mesa was interpreted using a process-based geomorphological framework, emphasizing the interaction between lithology, structure, climate, and surface processes. Observed landforms were analyzed in the context of post-impact degradation models developed for ancient impact structures in stable continental interiors. The combined use of field evidence and terrain analysis enabled reconstruction of relative stages of erosion and isolation of the mesa as a residual landform.

This integrated methodology allows for a robust assessment of post-impact erosion and landscape evolution, providing insights into the long-term geomorphic transformation of one of the oldest known impact structures on Earth.

5. **Integration and interpretation**

All spatial, structural, petrographic, and geochemical datasets were integrated into a unified GIS database. Comparative analysis was performed between remote-sensing interpretations, field observations, and laboratory results to test for impact-related signatures and to distinguish them from tectono-sedimentary or erosional origins. The combined dataset provides a basis for reconstructing the geological evolution of the Ramgarh structure and assessing the processes responsible for its present morphology.

Methodology

The methodology adopted in this study integrates field-based geomorphological investigations with terrain analysis to evaluate post-impact erosion and landscape evolution of the Central Inner Elevated (CIE) Mesa within the Dhala impact structure. The approach emphasizes direct observation of landforms and surface processes supported by spatial analysis of topographic data.

- **Field Mapping and Observations**

Detailed geomorphological field mapping was carried out across the CIE Mesa, its slopes, and adjoining low-relief surfaces. Traverses were conducted along radial and circumferential directions relative to the mesa to capture variations in erosional features and slope morphology. Observations focused on mesa margins, scarp characteristics, slope profiles, weathering intensity, and lithological boundaries. Structural elements such as joints and fractures were documented where exposed, as they exert strong control on erosion and slope retreat. Geographic coordinates of key geomorphic features were recorded using handheld GPS, and systematic photographic documentation was undertaken to support field interpretations.

- **Lithological and Surface Process Assessment**

Lithological characteristics of exposed units were examined to understand their role in differential erosion. Particular attention was given to contrasts in rock resistance, degree of weathering, and nature of erosional contacts between the mesa-forming units and surrounding terrain. Surface processes such as fluvial incision, rill and gully development, and sheet wash were identified and qualitatively assessed to evaluate their contribution to long-term denudation of the impact-modified landscape.

- **Topographic and Morphometric Analysis**

Topographic analysis was performed using Survey of India topographic sheets and Digital Elevation Model (DEM) data. Elevation profiles and slope gradients were extracted across the CIE Mesa and adjacent areas to quantify relative relief and slope asymmetry. **Drainage Analysis**

Drainage networks within and around the study area were mapped to evaluate their role in post-impact landscape modification. Stream patterns, incision styles, and alignment relative to lithological and structural features were analyzed to assess the influence of fluvial processes on mesa isolation.

Post-Impact Landscape Evolution

- **Lithological Control**
  - **Rock resistance**
  - **Differential weathering**
- **Structural Control**
  - **Joints and fractures**
  - **Guided erosion and drainage**
- **Surface Processes**
  - **Fluvial incision**
  - **Sheet wash**
  - **Slope retreat**
- **Climatic Influence**
  - **Monsoonal rainfall**
  - **Long-term denudation**
- **Resultant Landforms**
  - **CIE Mesa (erosional remnant)**
  - **Dissected slopes**
  - **Subdued crater morphology**

Fig.2.Methodology Flow Chart

Results

1. Geomorphological Characteristics of the CIE Mesa

Field investigations reveal that the CIE Mesa is a prominent erosional remnant characterized by a relatively flat summit surface and steep marginal slopes. The mesa rises distinctly above the surrounding low-relief terrain, indicating selective preservation due to lithological resistance. The margins are marked by sharp scarps, locally dissected by narrow gullies and short tributary channels. Evidence of slope retreat is observed in the form of talus accumulation and weathered rock fragments along the base of the mesa.[4]

Table 1. Morphological attributes of the CIE Mesa

Parameter	Observation
Planform shape	Sub-circular to elliptical
Summit surface	Broad, gently undulating
Margin morphology	Steep escarpments with minor re-entrants
Relative relief	Moderate to high compared to surrounding plains
Dominant landform	Erosional mesa (residual landform)

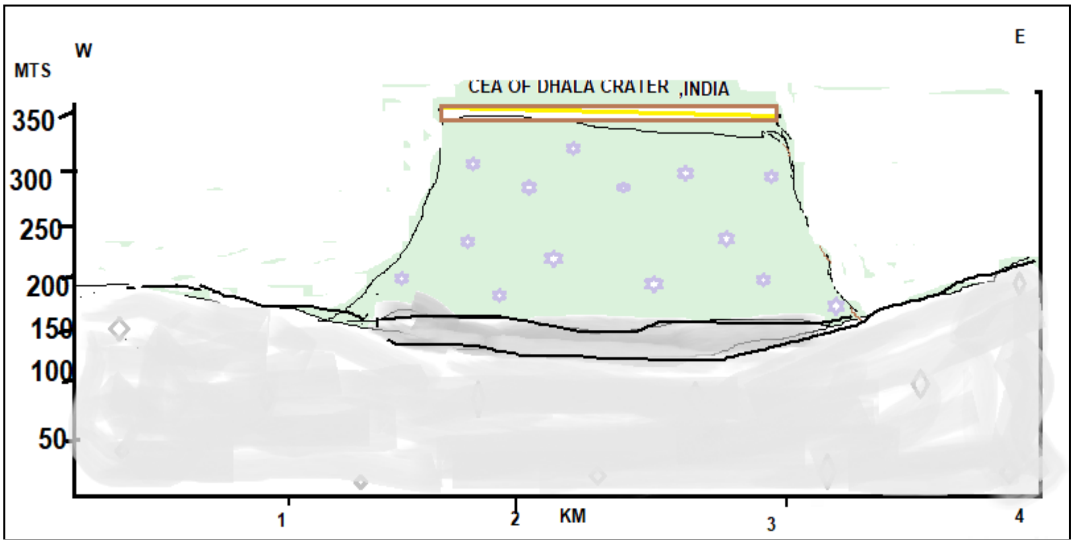

Fig.2. Geomorphological map of the Dhala impact structure showing the location of the CIE Mesa and major landform units

2. Lithological Control on Erosion

The summit and upper slopes of the CIE Mesa are composed of comparatively resistant sedimentary units, whereas the surrounding terrain exposes more weathered and fractured lithologies. This lithological contrast has played a significant role in differential erosion. Field observations show that erosion preferentially affects weaker units, resulting in the isolation of the mesa as a topographic high. Weathering profiles on the mesa top are comparatively thin, whereas deeper weathering and soil development occur on the surrounding plains[4].

Table 2. Relationship between lithology and erosional response

Lithological unit	Weathering intensity	Erosional expression
Mesa-forming unit	Low to moderate	Preserved summit and steep slopes
Surrounding units	Moderate to high	Lowered relief and pediment development
Fractured zones	High	Enhanced gully and channel erosion

3. Slope and Morphometric Analysis

Slope analysis indicates asymmetry in mesa margins, with steeper slopes occurring along structurally influenced directions. Gentle slopes dominate the summit area, whereas slopes increase sharply near the mesa edges. The presence of step-like breaks in slope suggests episodic retreat rather than uniform lowering. Relative relief measurements confirm significant denudation of the surrounding impact-modified terrain.[5]

Table 3. Slope characteristics of the CIE Mesa

Surface type	Slope angle (generalized)	Dominant process
Mesa summit	Gentle	Surface weathering
Upper slopes	Moderate	Sheet wash, weathering
Mesa margins	Steep	Scarp retreat, mass wasting
Surrounding plains	Very gentle	Planation and soil formation

4. Drainage Characteristics and Fluvial Incision

Drainage within the study area is dominated by short, structurally controlled channels originating near the mesa margins. These channels exhibit moderate incision and contribute to the dissection of mesa slopes. Radial to sub-radial drainage elements are locally preserved, reflecting the impact-related structural framework. Fluvial erosion has been instrumental in isolating the CIE Mesa by progressively removing surrounding material.

Fig.3. Rills and Gullies of CEA of Dhala crater

Table 4. Drainage characteristics of the study area

Parameter	Observation
Drainage type	Ephemeral to seasonal
Drainage pattern	Sub-radial to structurally guided
Incision depth	Shallow to moderate
Role in landscape evolution	Progressive isolation of mesa

5. Evidence of Post-Impact Denudation

Multiple indicators of long-term denudation are observed across the study area. These include subdued crater morphology, extensive pediment surfaces, and the absence of sharp primary impact features. The CIE Mesa represents a remnant of post-impact stratigraphy preserved due to favorable lithological and structural conditions, while the rest of the crater has undergone substantial erosion.[6]

Table 5. Indicators of post-impact erosion

Indicator	Interpretation
Reduced crater relief	Advanced stage of erosion
Mesa isolation	Differential denudation
Pediment development	Prolonged surface lowering
Dissected slopes	Active fluvial modification

Petrographic Evidence

Thin-section examination of sandstone samples from the rim and central uplift revealed micro-fracturing, mosaicism in quartz grains, and planar features aligned in multiple orientations. Several grains display undulose extinction, deformation bands, and intragranular cracks filled with secondary silica. Breccia samples exhibit angular to sub-angular clasts set in a fine-grained, recrystallized matrix. Although definitive planar deformation features (PDFs) were rare, the abundance of shock-like microstructures and cataclastic textures strongly supports high-strain, high-energy deformation consistent with an impact event rather than regional tectonism alone.[7,8,9,10,11]

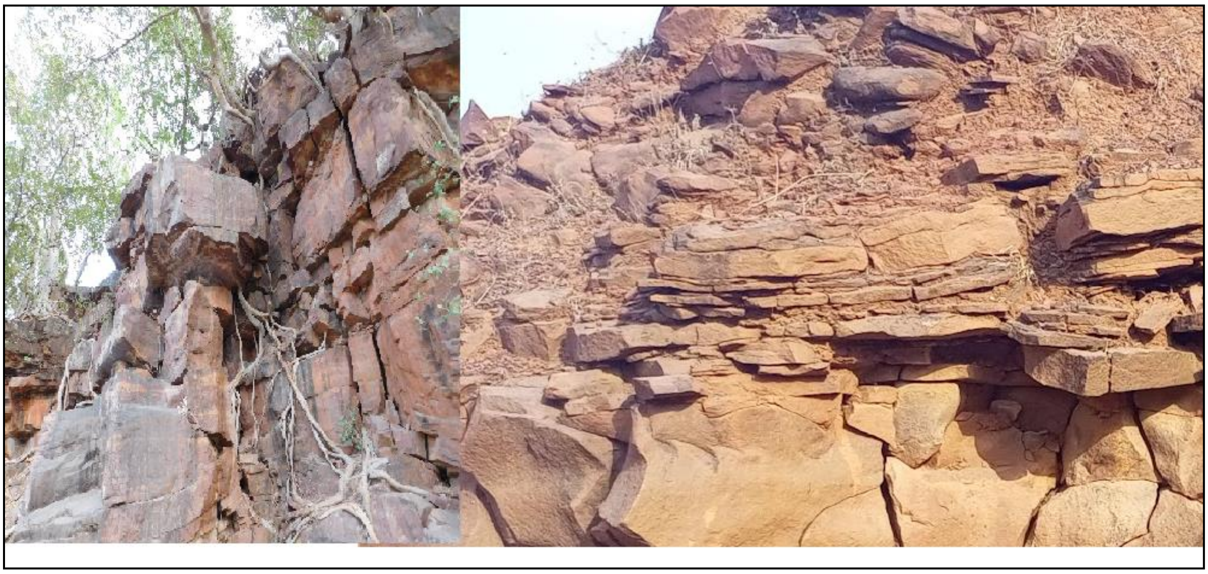

Fig.4 Image of CEA showing Rock structure of Dhala crater

Discussion

The geomorphological characteristics of the CIE Mesa provide important insights into the long-term degradation of the Dhala impact structure under stable cratonic conditions. The preservation of the mesa as a prominent residual landform indicates that post-impact landscape evolution has been governed primarily by differential erosion rather than tectonic reactivation. The flat summit surface and steep marginal slopes of the CIE Mesa are typical of erosional remnants formed where resistant lithological units overlie comparatively weaker and more weathered strata. This observation supports models of impact crater degradation in which selective preservation of resistant units occurs during prolonged denudation.

Fluvial incision has played a critical role in isolating the CIE Mesa from the surrounding terrain. The presence of short, structurally guided channels along the mesa margins suggests that pre-existing fractures and impact-induced structural weaknesses have influenced drainage development. Similar patterns have been documented in other deeply eroded impact structures worldwide, where radial or sub-radial drainage is partially preserved despite advanced erosion. The moderate incision depth observed in the study area indicates sustained but low-intensity fluvial activity operating over long geological timescales rather than episodic catastrophic erosion.[5]

The subdued expression of primary impact morphology within the Dhala structure reflects an advanced stage of post-impact modification. Features such as pediment development, reduced relief, and extensive weathering profiles collectively point to prolonged surface lowering. In this context, the CIE Mesa represents a geomorphic archive preserving elements of the post-impact stratigraphy rather than the original crater form. The results emphasize that ancient impact structures in Precambrian terrains may retain geomorphic significance long after diagnostic impact features become obscured.

The interaction between lithology, structure, and climate has been central to shaping the present landscape. Semi-arid to sub-humid monsoonal conditions have promoted chemical weathering and surface wash, while long-term tectonic stability has allowed erosional processes to operate uninterrupted. The findings from the CIE Mesa align with conceptual models of crater degradation that highlight the importance of slow, cumulative processes in modifying impact-generated landforms in continental interiors.

Limitations

Despite providing valuable insights into the post-impact landscape evolution of the CIE Mesa, the present study has certain limitations. The analysis is largely based on field observations and surface geomorphological evidence, and subsurface data are limited. The absence of high-resolution geophysical datasets restricts the ability to fully constrain subsurface geometry and the thickness of preserved crater-fill sequences. Additionally, quantitative erosion rates could not be directly estimated due to the lack of absolute age constraints on geomorphic surfaces.

The reliance on medium-resolution DEMs may also limit the detection of subtle micro-topographic features associated with early stages of crater degradation. Furthermore, climatic interpretations are inferred from regional patterns rather than site-specific paleoclimatic data. Future integration of high-resolution topographic data, geochronological techniques, and subsurface investigations would help overcome these limitations and refine interpretations of post-impact landscape evolution.

Conclusion

The present study demonstrates that the CIE Mesa within the Dhala impact structure is a product of long-term post-impact erosion and differential denudation operating under stable cratonic conditions. Field-based geomorphological evidence indicates that fluvial incision, slope retreat, and lithological resistance have collectively governed the isolation and preservation of the mesa as a prominent erosional remnant. The advanced stage of crater degradation observed at Dhala highlights the extent to which ancient impact structures can be modified and subdued by prolonged surface processes.

The findings underscore the importance of geomorphological investigations in understanding the evolutionary history of deeply eroded impact craters, particularly in Precambrian terrains where primary impact features are rarely preserved. The CIE Mesa serves as a valuable natural example of how impact-modified landscapes evolve over geological timescales, offering broader implications for recognizing and interpreting ancient impact structures on Earth and other terrestrial planets.

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Conflicts of interest

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

References

1. Agarwal, S., Pati, J.K., Reimold, W.U., and Koeberl, C. (2020). Evidence of shock metamorphism in sedimentary rocks from the Dhala impact structure, central India. Journal of Asian Earth Sciences, 194, 104112.
2. French, B.M., and Koeberl, C. (2010). The convincing identification of terrestrial meteorite impact structures: What works, what doesn't, and why. Earth-Science Reviews, 98, 123–170.
3. French, B.M., Koeberl, C., and Pati, J.K. (2017). Shock metamorphism in the Dhala impact structure, India. Meteoritics & Planetary Science, 52, 236–258.
4. Grieve, R.A.F., Reimold, W.U., Morgan, J.V., Riller, U., and Pilkington, M. (2008). Observations and interpretations of impact structures. Geological Society of America Special Paper, 384, 1–11.
5. Hergarten, S., and Kenkmann, T. (2015). The geomorphic degradation of impact craters: Insights from numerical modeling. Earth Surface Processes and Landforms, 40, 1026–1037.
6. Joshi, D., Pati, J.K., Reimold, W.U., Koeberl, C., and Sengupta, D. (2023). Geochronology and evolution of impact melt rocks from the Dhala impact structure, India. Precambrian Research, 388, 106965.
7. Kenkmann, T., Poelchau, M.H., and Wulf, G. (2014). Structural geology of impact craters. Journal of Structural Geology, 62, 156–182.
8. Melosh, H.J. (1989). Impact Cratering: A Geologic Process. Oxford University Press, New York, 245 pp.
9. Pati, J.K., Reimold, W.U., Koeberl, C., Schmitt, R.T., and Jourdan, F. (2010). The Dhala structure, Bundelkhand craton, India: A newly recognized Paleoproterozoic impact structure. Meteoritics & Planetary Science, 45, 522–541.
10. Pati, J.K., Agarwal, S., Reimold, W.U., Koeberl, C., and Sengupta, D. (2019). Petrology and geochemistry of impactites from the Dhala impact structure, India. Geological Journal, 54, 2145–2170.
11. Singh, Y., Pati, J.K., and Reimold, W.U. (2021). Geomorphic modification and erosion history of the Dhala impact structure, central India. Current Science, 121, 1483–1493.