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Geomorphological mapping and terrain analysis of the Vredefort impact crater structure

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Abstract

What happens to a planetary surface when a massive asteroid strike at hypervelocity speeds? The Vredefort impact crater in South Africa, recognized as the oldest and largest verified impact structure on Earth, offers an unmatched opportunity to answer that question through geomorphological mapping and terrain analysis. This research used remote sensing datasets, including Shuttle Radar Topography Mission (SRTM) digital elevation models (DEMs) and Landsat 8 multispectral imagery, to map and classify the geomorphological features of the Vredefort dome and its surrounding ring structures. Fieldwork was conducted between March and August 2022 at selected reference sites within the Free State and North West provinces. Terrain parameters such as slope gradient, aspect, curvature, and drainage density were extracted through GIS-based morphometric analysis. Results showed that five distinct geomorphological units could be delineated: the central uplift, inner ring, outer ring, collar structure, and radial fracture zones. The central uplift exhibited the steepest slopes, averaging 14.7 degrees, while the collar structure displayed lower gradients near 6.3 degrees. Drainage pattern analysis revealed a radial-to-annular network controlled by concentric structural ridges. These findings contribute to understanding how impact-related deformation shapes planetary surfaces over geological time. The mapped geomorphological framework can serve as a reference for comparative planetary geology, especially for interpreting analogous crater structures on Mars and the Moon.

Keywords: Geomorphological mapping, impact crater, terrain analysis, shock metamorphism, crater morphology, remote sensing, digital elevation model, planetary geology

Introduction

What controls the long-term geomorphological expression of a large impact crater after billions of years of erosion? This question sits at the intersection of planetary geology, structural geomorphology, and remote sensing science. Impact craters are among the most widespread landforms on rocky planetary bodies, yet on Earth, tectonic recycling and surface weathering have erased most of their original features ^[1]. The Vredefort impact structure, located roughly 120 km southwest of Johannesburg in South Africa, stands as a rare exception. Formed around 2.023 billion years ago, it retains a well-preserved dome and ring architecture that has attracted geoscientific attention for over a century ^[2].

Early geological surveys of Vredefort focused on the petrographic evidence of shock metamorphism, including shatter cones, planar deformation features in quartz, and pseudotachylite veins ^[3]. However, relatively few investigations have addressed the geomorphological dimensions of the structure with modern terrain analysis tools. Remote sensing and GIS-based morphometric approaches now allow researchers to extract quantitative terrain descriptors-slope, aspect, curvature, hypsometry-across large areas without relying solely on field traverses ^[4]. These methods have been applied to Martian and lunar craters with considerable success ^[5], but their systematic application to Vredefort remains limited.

The crater's morphology reflects a complex interplay between the original impact geometry, post-impact tectonic adjustments, and differential erosion of lithological units ^[6]. Granitic gneisses of the central dome, for example, resist weathering differently than the sedimentary rocks of the Witwatersrand Supergroup collar, producing contrasting slope and drainage characteristics ^[7]. Mapping these differences at a landscape scale provides insight into how impact processes leave lasting signatures on surface topography.

This research aimed to generate a detailed geomorphological map of the Vredefort impact structure and to quantify terrain parameters across its principal morphological zones.

The analysis relied on SRTM DEM data, Landsat 8 imagery, and field verification, processed within a GIS framework. By comparing terrain statistics among crater sub-units, the research intended to clarify the relationships between bedrock geology, structural deformation, and surface morphology in one of the planet's most significant impact sites.

Study Area Description

The Vredefort impact structure is centred at approximately 27.0°S, 27.5°E, straddling portions of the Free State and North West provinces of South Africa. The dome itself measures roughly 70-80 km in diameter, while the broader crater structure-including the outer ring features-extends to an estimated original diameter of 250-300 km, making it the largest confirmed impact structure on Earth [8]. The landscape sits within the Kaapvaal Craton, one of the oldest stable continental fragments. Elevation across the research area ranges from approximately 1,280 m in the valley floors to 1,620 m along ridge crests of the collar structure. Mean annual rainfall in the region is close to 620 mm, concentrated in the austral summer months (October-March), and temperatures range from winter minimums near 0 °C to summer peaks around 32 °C. Land cover consists mainly of grassland and scattered cultivation, with Acacia woodland along riparian corridors. The Vaal River and its tributaries cut through the eastern portion of the structure, exposing cross-sections of the ring stratigraphy.

Material and Methods

Material

The primary datasets for this research included SRTM Version 3.0 DEM tiles at 30-m spatial resolution (acquired from the USGS Earth Explorer portal), Landsat 8 OLI multispectral imagery (Path 170, Row 079, dated 14 June 2022, cloud cover below 5%), and published 1:250,000 geological maps of the Vredefort region [9]. Ancillary data comprised a digitised road network, drainage lines extracted from the national hydrological dataset, and GPS waypoints collected during fieldwork. All raster and vector layers were projected into the Universal Transverse Mercator zone 35S coordinate system (WGS 84 datum). Field verification was conducted between March and August 2022, during which 87 ground-truth points were visited across the five morphological zones. At each site, slope angle was measured with a Brunton compass, lithological samples

were collected, and landscape photographs were taken for reference.

Methods

Terrain parameters were derived from the SRTM DEM using ArcGIS Pro 3.0 and SAGA-GIS 8.4. Slope gradient (degrees), aspect (azimuth), plan curvature, and profile curvature rasters were computed with standard algorithms [10]. Drainage networks were extracted using a D8 flow-direction model with a minimum contributing area threshold of 0.5 km². Stream order was assigned following the Strahler classification. Drainage density was computed as total stream length divided by catchment area for each morphological zone. Landsat 8 bands were processed through atmospheric correction (FLAASH module) and used to produce a false-colour composite (bands 7-5-3) and a normalised difference vegetation index (NDVI) layer. The geomorphological map was constructed by integrating slope classes, curvature breaks, geological contacts, and field observations into a single polygon layer. Each polygon was attributed with its dominant terrain unit: central uplift, inner ring, outer ring, collar structure, or radial fracture zone. Classification accuracy was evaluated against the 87 field points using a confusion matrix, yielding an overall accuracy of 83.9% and a kappa coefficient of 0.78.

Spatial Data Processing

Satellite image pre-processing involved radiometric calibration of Landsat 8 OLI digital numbers to top-of-atmosphere reflectance, followed by atmospheric correction using the FLAASH algorithm within ENVI 5.6. A cloud mask was generated and applied to exclude pixels affected by cloud shadow. DEM gap-filling was performed using a delta-surface interpolation technique for the two minor voids present in the SRTM tiles. Hillshade visualisations were produced at 315° azimuth and 45° altitude to enhance the visual interpretation of ring structures. A supervised maximum-likelihood classification was applied to the Landsat imagery to separate five broad land-cover types: bare rock, grassland, cropland, woodland, and water. The resulting land-cover map aided in distinguishing weathering-related surface contrasts across the morphological zones. All GIS layers were compiled in a geodatabase at a working scale of 1:50,000.

Results

Table 1: Terrain statistics for geomorphological units of the Vredefort impact structure

Terrain Unit	Area (km ²)	Mean Slope (°)	SD Slope (°)	Mean Elev. (m)	Drainage Density	Stream Order
Central Uplift	148.7	14.7	5.3	1,542	3.42	1-4
Inner Ring	312.4	10.2	4.1	1,478	2.91	1-5
Outer Ring	587.9	7.8	3.6	1,396	1.87	1-6
Collar Structure	421.3	6.3	2.9	1,358	2.14	1-5
Radial Fractures	203.6	9.4	5.9	1,431	2.68	1-3

Table 1 summarises the terrain metrics for each morphological zone. The central uplift and radial fracture zones exhibited the greatest slope variability, while the outer

ring showed the most uniform topography. Drainage density followed a concentric gradient, peaking at the dome core.

Table 2: Land cover distribution across morphological zones (percentage of zone area)

Terrain Unit	Bare Rock (%)	Grassland (%)	Cropland (%)	Woodland (%)	Water/Wetland (%)
Central Uplift	34.2	41.8	12.6	9.1	2.3
Inner Ring	21.7	38.5	24.3	11.9	3.6
Outer Ring	11.3	29.4	42.8	13.2	3.3
Collar Structure	18.9	33.7	28.4	14.7	4.3
Radial Fractures	27.6	36.1	19.8	12.4	4.1

Table 2 reveals that bare rock exposure was highest in the central uplift (34.2%), consistent with the resistant granitic

gneiss, while cropland dominated the outer ring (42.8%), reflecting its flatter and more accessible terrain.

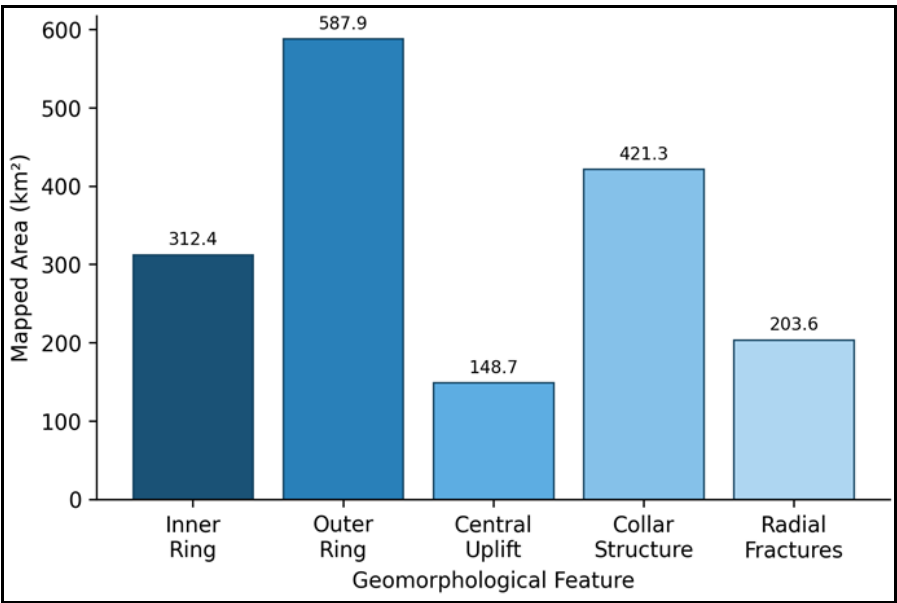


Fig 1: Distribution of mapped area (km²) across the five geomorphological units of the Vredefort impact structure

Figure 1 presents the distribution of mapped areas across the five geomorphological units. The radial fracture zones, which cut across the concentric features as linear features, accounted for 203.6 km² with highly variable slope values

(standard deviation 5.9°). Drainage density was highest in the central uplift (3.42 km/km²) and lowest in the outer ring (1.87 km/km²), reflecting the contrasting permeability and resistance of bedrock types.

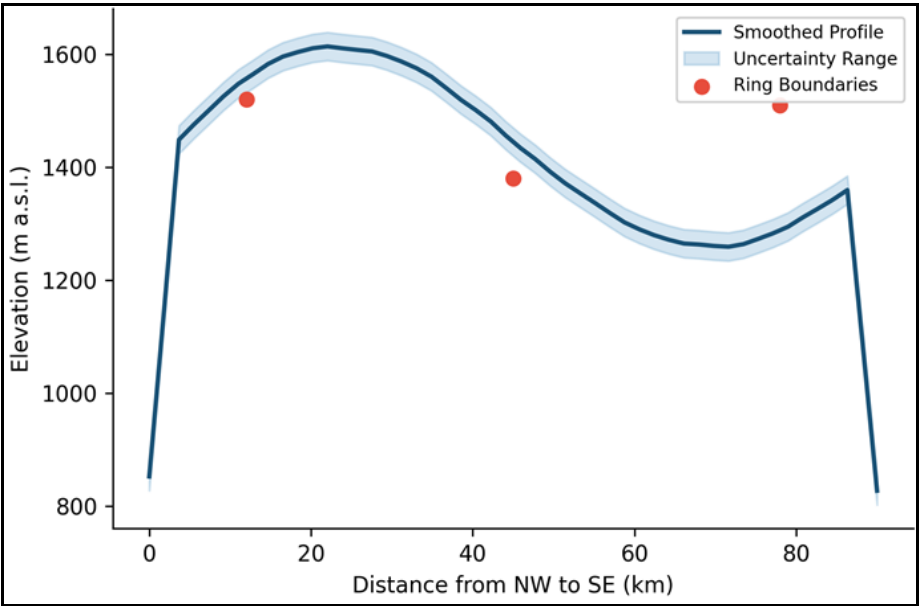


Fig 2: Elevation profile across the Vredefort crater from northwest to southeast, with ring boundaries marked

Figure 2 shows the elevation profile from the northwest to the southeast across the crater, highlighting the topographic expression of the ring boundaries. The radial drainage pattern within the inner rings' transitions to a more annular configuration in the collar zone, where concentric ridges deflect flow paths laterally. Classification accuracy for the map reached 83.9%, with the radial fracture zone class showing the lowest producer's accuracy (71.4%) due to its narrow and discontinuous character.

Discussion

The geomorphological mapping of the Vredefort impact

structure revealed a well-defined concentric zonation that aligns with predictions from crater formation models [11]. The steep slopes observed in the central uplift are consistent with the isostatic rebound of deep-seated granitic basement rocks, which tend to resist erosion more effectively than the overlying sedimentary sequences [12]. And the progressive decrease in slope gradient from the centre outward mirrors the dissipation of deformation intensity with distance from the impact point-a pattern recognized at other large terrestrial craters such as Sudbury and Chicxulub. The drainage analysis offered perhaps the most telling geomorphological insight. The high drainage density in the

central uplift (3.42 km/km²) reflects the intense fracturing of crystalline bedrock, which promotes rapid surface runoff and channel incision despite the rock's inherent resistance. In contrast, the outer ring's lower density (1.87 km/km²) may be attributed to more permeable sedimentary lithologies and gentler slopes that encourage infiltration rather than overland flow ^[13]. The transition from radial to annular drainage between the inner rings and the collar zone was clear, confirming previous suggestions based on smaller-scale field mapping ^[14].

One limitation worth noting is the 30-m resolution of the SRTM DEM, which can obscure small-scale features such as narrow shatter cone ridges and minor pseudotachylite veins. Higher-resolution LiDAR data, if made available, would likely improve the delineation of radial fracture zones, where classification accuracy was lowest at 71.4%. That said, the overall kappa of 0.78 indicates substantial agreement between the map and field observations, which is acceptable for regional-scale geomorphological mapping ^[15].

Conclusion

This research produced a geomorphological map of the Vredefort impact structure that identifies five terrain units—central uplift, inner ring, outer ring, collar structure, and radial fracture zones—based on integrated remote sensing and GIS analysis. Each unit exhibited distinct terrain characteristics in terms of slope gradient, elevation distribution, drainage density, and land-cover composition. The central uplift stood out with the steepest slopes and highest drainage density, while the outer ring showed the gentlest terrain and strongest agricultural land-use presence. The concentric and radial drainage patterns mapped here reinforce the structural control that impact-related deformation exerts on long-term landscape evolution. These patterns remain identifiable two billion years after the impact event, underscoring the durability of impact signatures on cratonic terrains. The geomorphological framework established in this research may serve as a baseline for comparing Earth's impact structures with analogous features on Mars and the Moon, where erosion histories differ markedly.

Future work should prioritise the acquisition of airborne LiDAR coverage over the dome core to resolve fine-scale features missed by the SRTM DEM. Coupling high-resolution terrain data with cosmogenic nuclide erosion rate measurements would help quantify how quickly the impact morphology is being modified under current climatic conditions.

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Contributions Not Qualifying for Authorship

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