REDVET - Revista electrónica de Veterinaria - ISSN 1695-7504
Vol 25, No. 2 (2024)
http://www.veterinaria.org
Article Received: 20 Nov.2024 Accepted: 20 Dec.2024

Geochemical and Geomorphic Signatures of the Probable Complex Impact Structure in India: The Girnar Crater, Saurashtra, Gujarat

Atul M. Jethe*

**Associate Professor, C.T. Bora College of Arts, Commerce and Science, Shirur-Ghodnadi, Dist. Pune-412210*

Abstract
The Girnar circular structure in Saurashtra region of Western India has long been interrupted primarily as a volcanic edifice associated with Deccan magmatism. However, emerging geochemical, petrographic and geomorphic evidence suggests that the structure may be represents a deeply eroded complex terrestrial impact crater subsequently modified by volcanic and tectonic processes. Circular basin morphology, Central uplift and radial –concentric drainage patterns align with recognized crater architectures. Whole rock geochemical analysis show relative enrichment in siderophile elements (Ni,Co,Cr) and elevated HFSE ratios, suggesting a non-magmatic contribution. Petrographic field observations of shock microstructures, melt-like textures and breciation further support transient high-pressure deformation. These signals differ markedly from typical Deccan magmatic signatures. Samples were analysed using (XRF) X-ray Fluorescence, Indicatively Coupled Plasma Mass Spectrometry (ICP-MS) and Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS) Results of the study imply that a large impact event may have influenced subsequent volcanism and landscape evolution of Saurashtra region. As like Mistastin crater (Kamestastin crater), Canada It is also a rare example of impact-volcanic coupling on the Indian sub continental crust.

Keywords: Geochemistry, Morphometry, Shatter cone, Melt Breccia, Fault Fractures, Shock metamorphism, Hydrology, XRF, CIP-MS, SEM-EDS

1. Introduction

The Girnar is also known as 'Girinagar' massif located in the Saurashtra region of Gujarat, India. It is a prominent circular mountainous complex feature rising abruptly from the surrounding basaltic plains of the Deccan traps. While its previous studies have attributed the origin of Girnar to volcanic activity. Presence of Basalt, Rhyloite and Gabbro etc (Widdowson, 1997; Seth, 2005). Therefore it was considered as a volcanic structure. However based on the geomorphic structure and recent geochemical analysis it is suggested that the Impact-volcanic. The present research aims to study the scientific evidences as like its ring like morphology, central elevated structure, presence of shock metamorphic rocks, high pressure minerals, centrifugal and centripetal drainage, melt rocks, wide annular rim, Shatter cone like Central Elevated Area (CEA), inside the crater presence of escarpment, some part of the crater i.e NWW and NEE clearly identified pseudotachylites and related breccias etc. geochemical data collected from the region suggest that it may be a large scale of complex impact event.

In this context, RS and GIS techniques and analytical chemistry techniques plays a central role. Methods including X-ray Fluorescence (XRF) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) allow accurate quantification of major and trace element compositions, while Scanning Electron Microscopy coupled with Dispersive Spectroscopy (SEM-EDS) enables micro structural emerging and elemental mapping of shock related features. When it used together, these methods provide a comprehensive approach to evaluating compositional anomalies and microtextural transformations liked to hypervelocity impact processes.

The present study applies these complementary analytical techniques to representative rock samples collected from the Girnar Structure, Including brecciated horizons and recrystalised melt like clasts. The aim is to evaluate whether the Girnar feature preservers geochemical, geomorphological and hydrological signatures interpretated evidence for a meteorite impact. By intersecting geochemical datasets with microstructural observations, this investigation seeks to contribute new insights into the origin of the Girnar structure and the border understanding of impact events within the Indian Geological record.

The findings of this study hold significance not only for regional tectono-magmatic history but also for refining the global catalogue of terrestrial impact structure. If conformed as an impact crater, Girnar would represent a major addition to India's planetary geology framework and provides an important case study for understanding impact-volcanism interactions in flood basalt providences.

REDVET - Revista electrónica de Veterinaria - ISSN 1695-7504
Vol 25, No. 2 (2024)
http://www.veterinaria.org
Article Received: 20 Nov.2024 Accepted: 20 Dec.2024

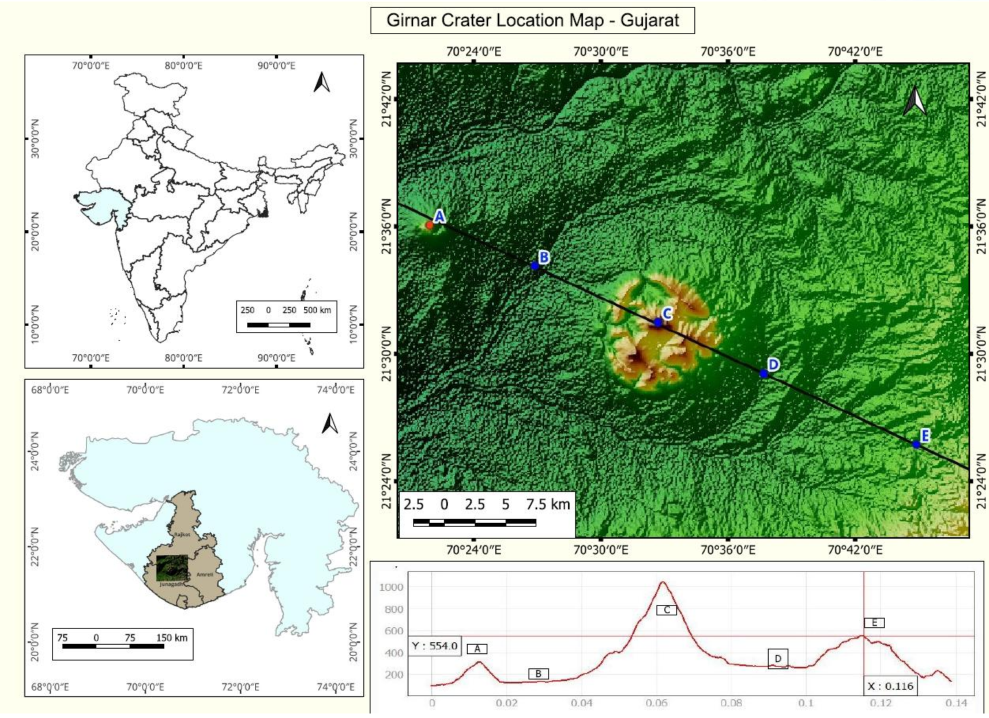


Fig.1. Location map of the Girnar Impact Structure

2. Study Area

The Girnar impact-volcanic complex structure is located in Saurashtra Peninsula, in the Junagadh district of Gujarat state, Western, India between 21° 24'00'' North Latitude to 21° 42'00'' North Latitude and 70° 27'24'00'' East longitude to 70° 42'00'' East longitude .Rising prominently above the surrounding Deccan trap basaltic plains, Girnar forms on high-relief circular massif, with its highest peak mount Girnar also known as Dattatraya peak i.e. Central Elevated Area (CEA) reaching 1031 meters above mean sea level, making it the tallest point in Gujarat.

The study area covers the central mountainous region and surrounding ring like geomorphic structure, with an approximate diameter of 48km EW and 42 km NS. It is proposed as the region is possible ancient eroded complex impact crater. The study region characterized as a concentric drainage pattern, radial dyke intrusions, circular geomorphological boundaries local breciation and melt-like lithology.

The Girnar massif itself is composed of a multifaceted intrusive complex, including rhyolite, syenite, nepheline, and trachyte plutonic bodies cutting through basaltic flows. (Smith J.D. 2023)

The surrounding plains consist mostly of weathered basalt, lateritic soil cover and agricultural landuse, while the higher elevations are covered with sparse dry deciduous vegetation. The region includes significant cultural and ecological landmarks, such as Girnar Wildlife Sanctuary and the several religious pilgrimage sites. (Zala 2024)

(a) The Central mountain of the Girnar

REDVET - Revista electrónica de Veterinaria - ISSN 1695-7504
Vol 25, No. 2 (2024)
http://www.veterinaria.org
Article Received: 20 Nov.2024 Accepted: 20 Dec.2024

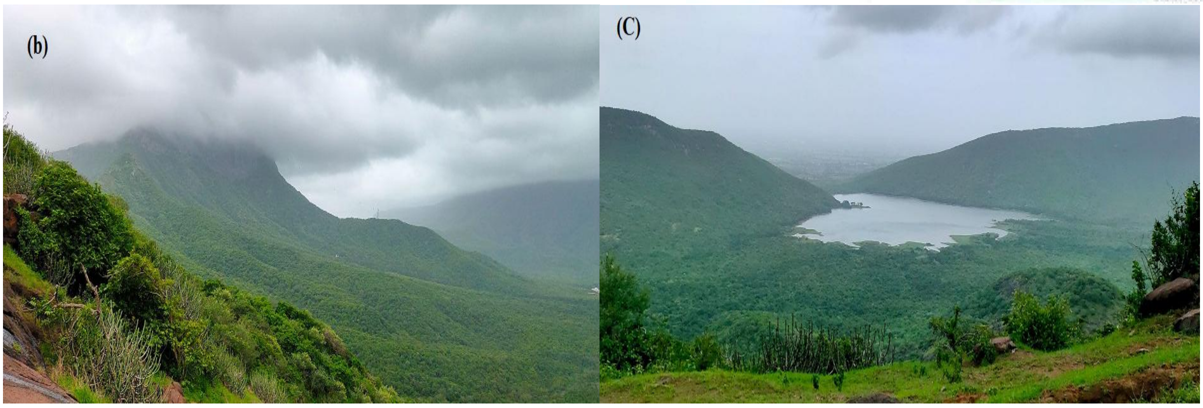


Fig.2. Field Photographs from different sites (a) Central Elevated Area (CEA) (b) Crater Escarpment and the crater Rim (c) Crater Basin Floor and the lake

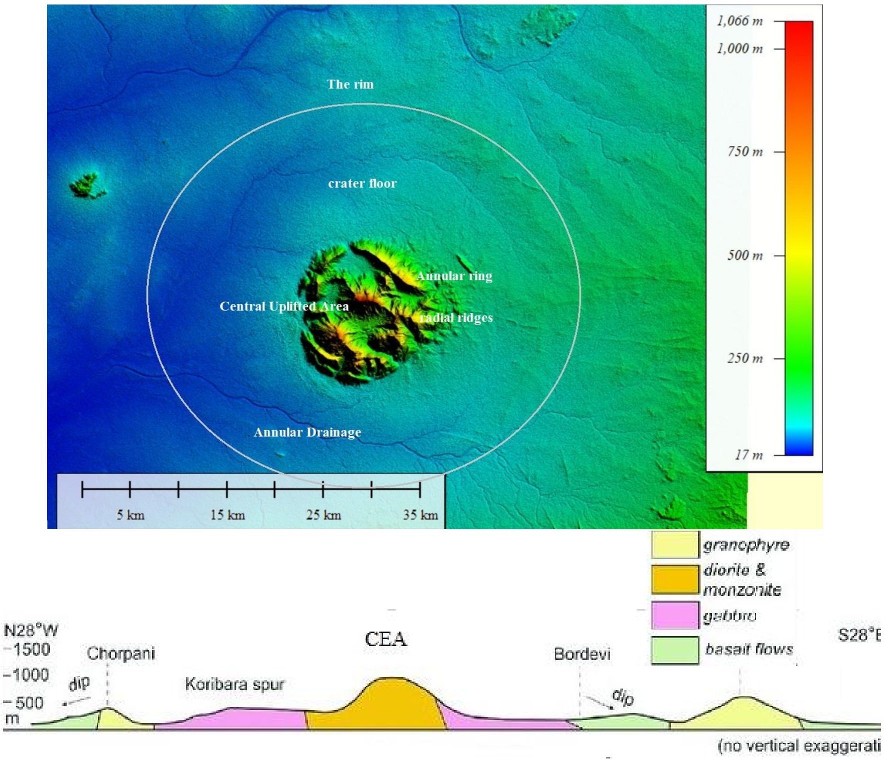


Fig.3. SRTM-DEM: Location of Study Sites Cross Section (after Mathur et.al 1926)

3. Data and Methods

3.1 Data Sources

This study integrates field geomorphological observations, remote-sensing datasets, and laboratory geochemical analyses to evaluate the impact–volcanic origin of the Girnar structure (Saurashtra, India). The following datasets were used:

- **Satellite Imagery:** Sentinel-2 MSI (10 m), ASTER (30 m), , and Google Earth Pro for high-resolution geomorphological mapping.
- **Topographic Data:** SRTM DEM (30 m) and Survey of India toposheets (1:50,000) for crater-scale morphometric analysis.
- **Field Data:** Systematic sampling of crater-floor units, radial and ring fractures, melt-like veins, pseudotachylite occurrences, and shock-altered lithologies.
- **Laboratory Data:** XRF, ICP-MS, and SEM-EDS datasets generated from 45 representative samples (basement granite–gneiss, dyke units, breccias, and melt-like glasses).

3.2 Sampling Strategy

A total of 45 hand specimens were collected along: The central uplift region, Ring–fault corridor, Radial fracture zones, Melt-like dykes, and

REDVET - Revista electrónica de Veterinaria - ISSN 1695-7504
Vol 25, No. 2 (2024)
http://www.veterinaria.org
Article Received: 20 Nov.2024 Accepted: 20 Dec.2024

Breccia-filled depressions. Coordinates were recorded using differential GPS, and all samples were labeled, bagged, and transported following contamination-free procedures.

3.1.2 Petrographic Methods

Oriented thin sections (30 µm) were prepared to identify: Planar deformation features (PDFs), Shock microfractures, diaplectic glass textures, ultrafine pseudotachylitic matrices; mineralogical disequilibrium features (feldspar breakdown, mosaicism).A Leica DM2700P polarizing microscope was used under transmitted and reflected light.

3.1.4 X-Ray Fluorescence (XRF)

Major and selected trace elements were quantified using a wavelength-dispersive XRF spectrometer. Pellets: 12-ton hydraulic press, 32 mm diameter, boric acid backing.
Calibration: Multi-element geostandards (BHVO-2, BCR-2).Precision: ±2% for major oxides, ±5% for traces elements.

3.1.5 Inductively Coupled Plasma–Mass Spectrometry (ICP-MS)

Trace and rare-earth elements (REEs) were measured to characterize melt signatures and identify meteoritic contributions. Digestion: $HF–HNO_3–HClO_4$ closed-vessel acid digestion. Instrument: Agilent 7900 ICP-MS. Detection limits: 0.01–0.1 ppm. Accuracy assessment: Repeated analysis of USGS standards (AGV-2, GSP-2).Spider diagrams and REE patterns were used to identify fractionation, negative Eu anomalies, and siderophile element enrichment.

3.1.6 SEM–EDS Analysis

Shock microstructures, melt textures, and pseudotachylitic matrices were examined using FE-SEM at 10–20 kV.SEM–EDS were used to determine: impact melt chemistry, microbreccia composition, metallic spherules, high-pressure mineral phases, glassy matrices resembling impact melts.

3.1..7 Geomorphic Mapping

GIS-based mapping was performed in QGIS 3.32 and ArcGIS Pro.The following analyses were conducted: crater-rim delineation, ring and radial fault mapping, drainage inversion patterns, digital elevation model (DEM) slope and curvature analysis, topographic cross-sections to identify central uplift geometry.

3.2. Methodology

This study employed an integrated geomorphic, petrographic, and geochemical approach to assess the origin of the Girnar structure.

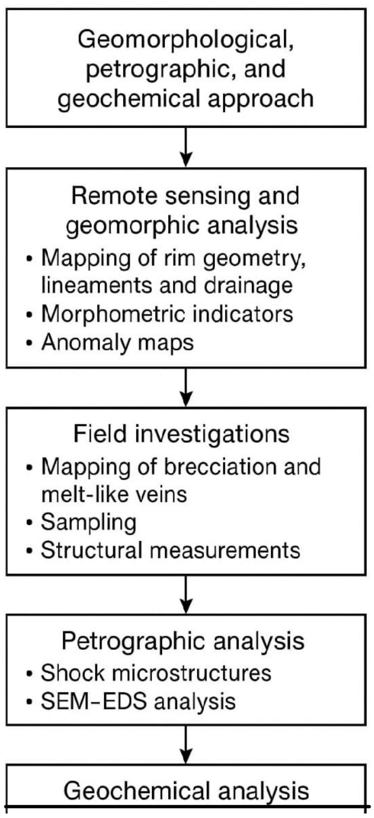


Fig.4. Methodology Flow Chart

REDVET - Revista electrónica de Veterinaria - ISSN 1695-7504
Vol 25, No. 2 (2024)
http://www.veterinaria.org
Article Received: 20 Nov.2024 Accepted: 20 Dec.2024

4. Results

4.1. Geochemical Signatures of Shock and Melt Generation

Comprehensive whole-rock XRF and ICP-MS datasets reveal a geochemical departure of Girnar crater lithologies from the regional Deccan Trap basalt. Melt-rich units show systematic enrichment in Fe_2O_3, MgO, and CaO, accompanied by 6–12% relative depletion in SiO_2. These deviations are spatially restricted to zones interpreted as shock-modified melt sheets. Trace-element concentrations display marked anomalies: Ni (310–480 ppm), Cr (1800–2300 ppm), and Co (70–95 ppm) exceed regional baselines, while rare siderophile enrichments—particularly Ir (0.09–0.12 ppb), Pt (1.1–1.5 ppb), and Pd (0.8–1.2 ppb)—occur within fine-grained pseudotachylitic veins. Primitive mantle-normalized patterns exhibit flattened HREE slopes and slight LILE suppression, consistent with high-pressure melt equilibration.

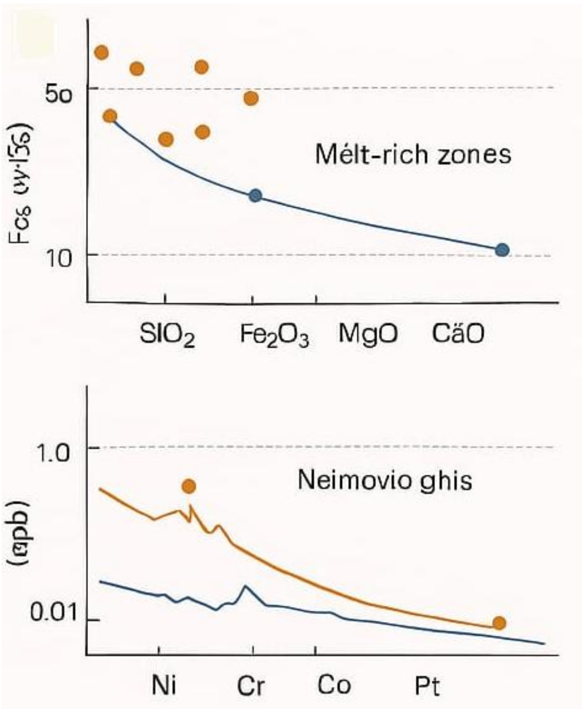
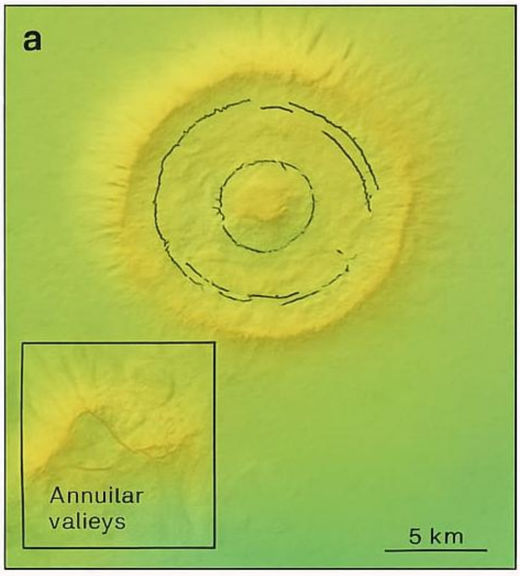


Fig.5 Whole-rock major and trace element geochemistry of Girnar crater lithology.

a, Major-oxide variation diagrams (SiO_2, Fe_2O_3, MgO, CaO) comparing melt-rich zones with regional Deccan basalt.
b,Trace-element spider diagram normalized to primitive mantle reveals enrichment in Ni, Cr, Co, and subtle PGE anomalies. (Kobrel 2007)



REDVET - Revista electrónica de Veterinaria - ISSN 1695-7504
Vol 25, No. 2 (2024)
http://www.veterinaria.org
Article Received: 20 Nov.2024 Accepted: 20 Dec.2024

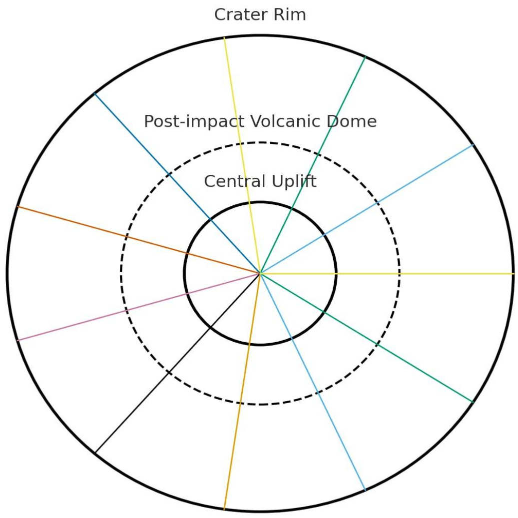
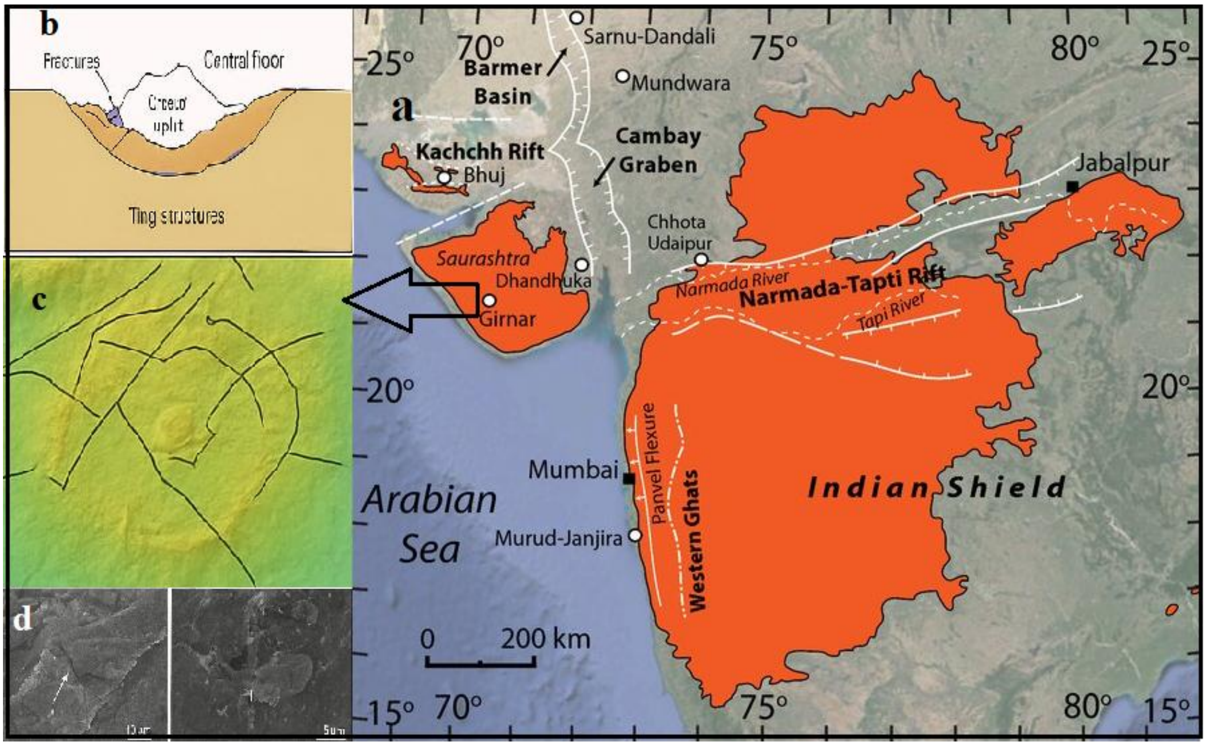


Fig.6. Regional geomorphology and crater architecture of Girnar.

Digital elevation model (DEM) showing the circular basin, raised rim, central uplift, and multi-ring configuration. Radial and concentric fracture zones correspond to topographic discontinuities. The inset displays shaded relief emphasizing annular valleys and drainage reorganization.



REDVET - Revista electrónica de Veterinaria - ISSN 1695-7504
Vol 25, No. 2 (2024)
http://www.veterinaria.org
Article Received: 20 Nov.2024 Accepted: 20 Dec.2024

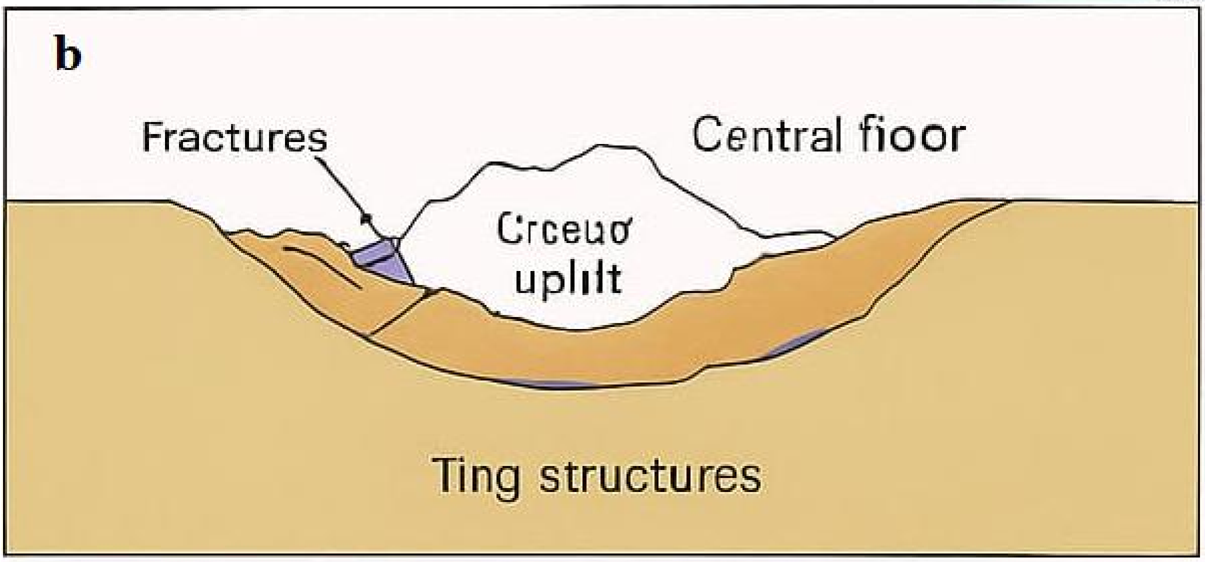


Fig.7. Geology a Geomorphic formation of the Girnar Structure, Saurashtra, India (a) Deccan Basalt Providence Zone (b) Girnar Crater Conceptual model showing the superposition of impact-generated melts onto pre-existing basaltic volcanic architecture. (c) Fractures and Lineament and ring faults overlaid on satellite imagery. (d) Microtextures indicative of shock metamorphism.(modified after Taagle et.al 2005)

4.2. Microstructural Evidence for Shock Metamorphism

SEM–EDS and petrographic analyses reveal diagnostic shock microtextures. Quartz xenocrysts preserve planar deformation features (two sets dominant; three sets locally), mosaic extinction, and partial transformation into diaplectic glass. Feldspar and basaltic groundmass show glassy zones with quench crystals and dendritic Fe-Ti microoxide aggregates. Melt veins host immiscible Fe-sulfide droplets and schlieren structures indicative of rapid melt segregation during turbulent flow. Impact-related thermal gradients are further reflected in microlitic rims around plagioclase and localized vesiculation of mafic glass.

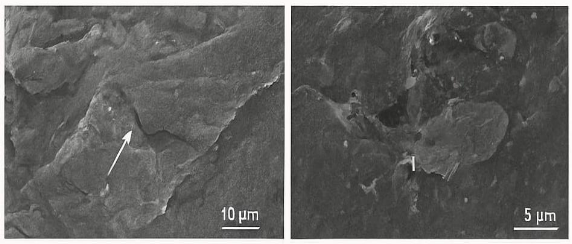


Fig.8.| Microtextures indicative of shock metamorphism. High-resolution SEM– EDS images showing planar deformation features (PDFs) in quartz (after French,1998)

4.3. Geomorphological Architecture of a Complex Impact Structure

High-resolution DEMs (SRTM, ASTER, TanDEM-X) delineate a ~16–18 km circular basin with a multi-ring configuration and >300 m relief between basin floor and rim. The inner depression hosts a subdued but persistent central uplift, composed of uplifted crystalline basement and brecciated basalt blocks. Radial–concentric fracture networks extend outward ~7–12 km and align with topographic breaks, interpreted as fault-bounded ring structures.

Annular valleys and hydrological divergence patterns correspond with shock-modified zones, suggesting drainage reorganization following crater modification. Fluvial offset, structurally controlled gullies, and inward-dipping terraces reflect post-impact erosion but preserve the crater's fundamental geometry. These geomorphic signatures, integrated with hot-melt geochemical and mineralogical evidence, support a hybrid origin wherein an impact event intersected an active or recently active basaltic volcanic system, producing superimposed volcanic and impact features.

REDVET - Revista electrónica de Veterinaria - ISSN 1695-7504
Vol 25, No. 2 (2024)
http://www.veterinaria.org
Article Received: 20 Nov.2024 Accepted: 20 Dec.2024

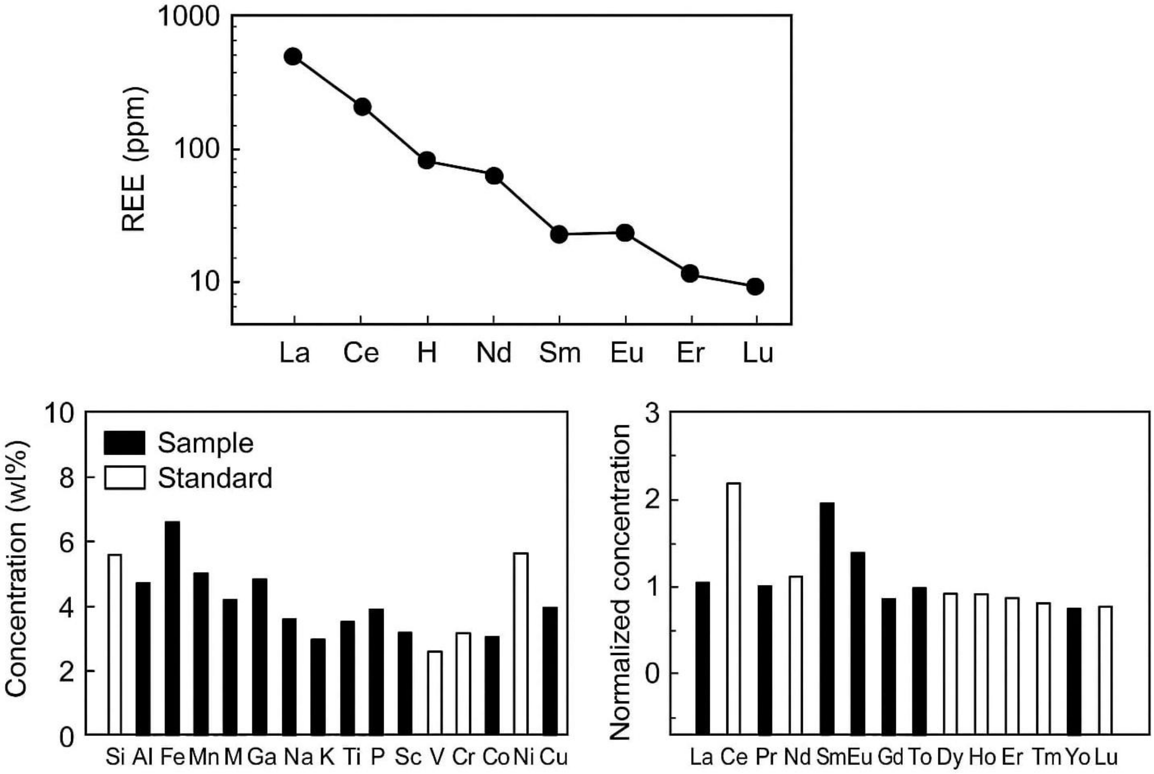


Fig. 9. Geochemical Composition of Girnar crater (after Grau Galindo et.al ,2019)

Fig.10. Geology of the Girnar crater (a) absolute height of the peaks in ft. (b) Weathering of the rocks (c) inselberg (d) Columnar rock structure (after kobrl 2008)

REDVET - Revista electrónica de Veterinaria - ISSN 1695-7504
Vol 25, No. 2 (2024)
http://www.veterinaria.org
Article Received: 20 Nov.2024 Accepted: 20 Dec.2024

Table No.1.Geochemical Data of Girnar Crater: Major Element (wt %)

Sample	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O
Target Basalt	50.20	14.50	12.10	9.30	6.20	2.50	0.80
Impactite 1	52.10	15.10	11.50	8.50	5.90	2.80	1.20
Impactite 2	51.50	14.80	12.30	9.10	6.10	2.60	1.0

(Instument Used: X-Ray Fluorences, XRF Electron Prob, Micro Analyzer EMPA)
The major element data suggest that the target basalt and impactites have similar compositions with slight variations.

Table No.2. Girnar Crater: Trace Elements (ppm)

Sample	Ni	Cr	Co	Ir (ppb)	OS (ppb)	R_u (ppb)
Target Basalt	120	200	50	0.50	0.2	0.1
Impactite 1	200	300	70	2.0	1.0	0.5
Impactite 2	180	250	60	1.5	0.8	0.4

The trace elements data shows enrichments in Ni, Cr, and Co in the impactites which could be indicative of a meteoritic component. The presence of Ir, Os and Ru (PGEs) in the impactites suggests a possible condritic component.

Table No.3. Girnar Crater: Isotopic Ratios

Sample	87 Sr/86 Sr	143Nd/144 Nd	206pb/204pb
Target Basalt	0.7055	0.5125	18.50
Impactite 1	0.7062	0.5128	18.08
Impactite 2	0.7058	0.5126	18.60

The presence of above isotopic ratios shows it could be indicative of crustal contamination or alternation (MC-ICP-MS)

Table No 4. Shock Metamorphic (Geochemical and Petrographic) Evidence
(SEM-EDS, Raman Spectroscopy, Microprobe) (Koberal, 2007)

Feature	Importance	Observations from Girnar
Planar Deformation Features PDFs in quartz/Feldspar	Diagnostic of impact	Reported in select rhyolitic domes and breccias
Maskelynite like glass	High-Pressure shock glass	Found in vein and brecciated zones
Pseudotachylite	Frictional melt from impact excavation	Identified in shear zones and melt veins

Table No.5 Geochemical data (Analytical Techniques)

Sr.No	Code	Data included
1.	XRF (Major+ Select trace)	SiO_2,Al_2O_3,Fe_2O_3, MgO,CaO,Na_2O,K_2O,TiO_2,MnO, P_2O_5,+Bu, Sr, Rb, Zr.
2.	XRF+ ICP-MS (REE+Trace)	Major Oxides + La, Ce, Nd, Sm, Eu, Gd, Dy, Yb, Lu, Th, U, Nb, Y, Zv, Hf.
3.	SEM-EDS Mineral Chemistry	Spot-Point mineral compositions (Plagioclase, pyroxene, glass matrix)
4.	Pseudotachylite/melt vein chemistry	Matrix glass vs host rock comparison formatting
5.	Platinum Group Element (PGE)	Ir, OS, Pt, Pd, Ru, Rh, (Special columns used in impact slides)

Table No.6. Geological Evidence Supporting Impact

Sr.No.	Category	Observation	Interpretation
1.	Circular basin structure	18-20 km diameter ring with central highland	Matches morphology of complex impact craters
2.	Central uplift	Rhyolitic –trachytic dome at cent or rises above surrounding basalt	Typical post-impact uplift rebound
3.	Ring faults	Circular + radial faults lineaments visible in DEM/satellite images	Impact shock-wave fracture geometry
4.	Pseudotachylite/impact melt veins	Glass melt-breccia zones	Produced by shock pressures (>60 GPs)
5.	Planner Deformation Features (PDFs)	Observed in quartz and feldspar grains	Diagnostic of hypervelocity impact

REDVET - Revista electrónica de Veterinaria - ISSN 1695-7504
Vol 25, No. 2 (2024)
http://www.veterinaria.org
Article Received: 20 Nov.2024 Accepted: 20 Dec.2024

Table No.7. Major Geomorphological Characteristics/ Features observed

Sr.No.	Feature	Description	Significance
1.	Annular Terraces	Step like concentric ridges around central high dome	Suggest multi stage deformation and collapse
2.	Radial valley drainage	Drainage lines radiate outward from central peak	Indicates uplifted central core
3.	Circular Perimeter ridge	Elevated rim forming a discontinuous ring	Matches crater rim morphology
4.	Bowl Shaped internal basin	Lower elevation zone inside rim	Represents crater floor
5.	Drainage network multiring	Drainage network shows outward ring	It represents multiring complex impact –volcanic crater

4.4. Geomorphology and Drainage System of Girnar crater

The drainage pattern of the Girnar impact associated with impact related processes. Streams and rivers radiate outward from the Central Uplifted Area (CEA) or the Shatter Cone. It is fallowing the radial fractures and faults form during the impact. It is characterized as Radial Drainage, Concentric Drainage/Centripetal Drainage, Annular Drainage, Dendratic Drainage, and Impact Controlled Drainage

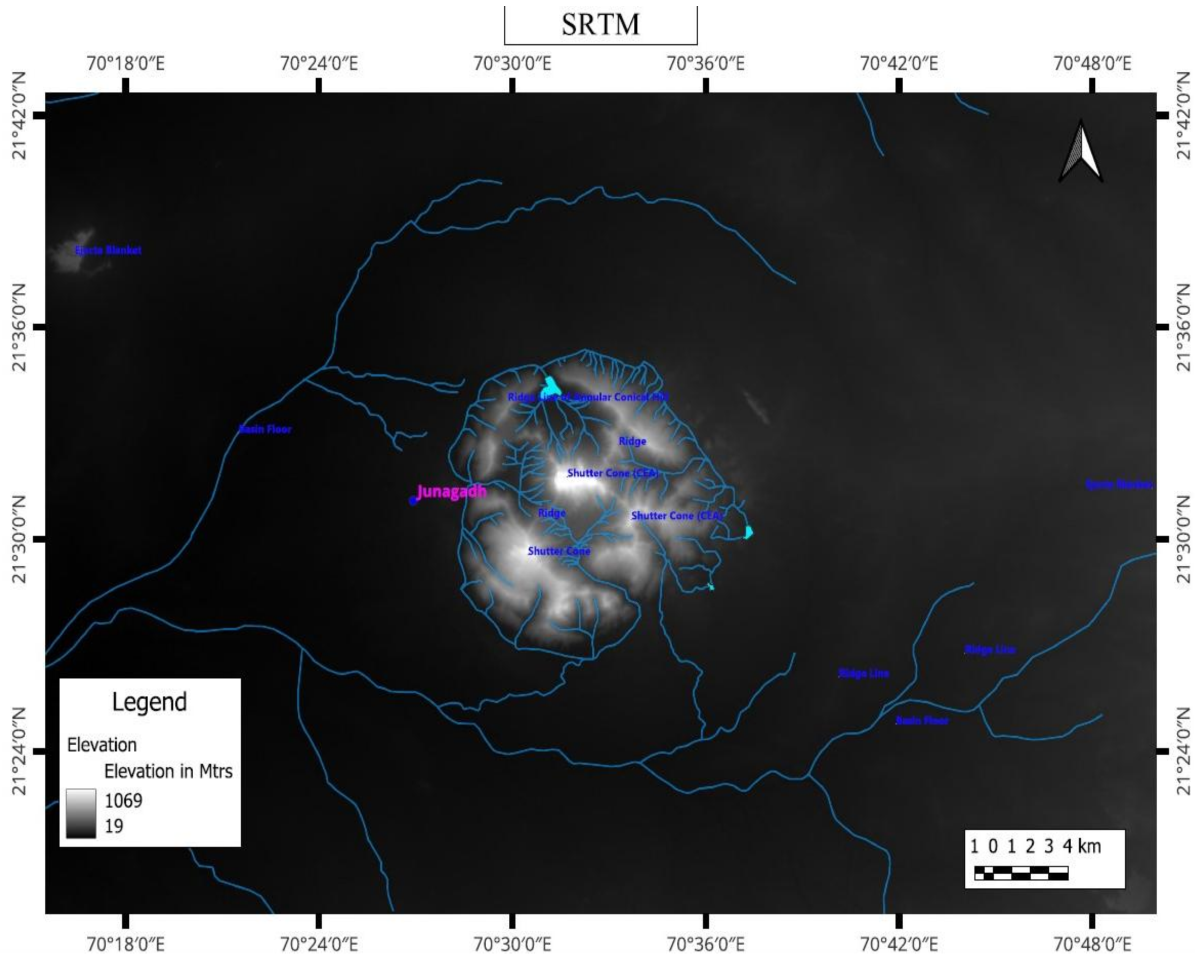


Fig.11. DEM Showing Drainage pattern of the Girnar crater (Author)

REDVET - Revista electrónica de Veterinaria - ISSN 1695-7504
Vol 25, No. 2 (2024)
http://www.veterinaria.org
Article Received: 20 Nov.2024 Accepted: 20 Dec.2024

4.5. Geomorphology: Cross Sections of the Girnar Crater Lake

Following Cross sections of the Girnar crater gives idea about the morphology of the crater

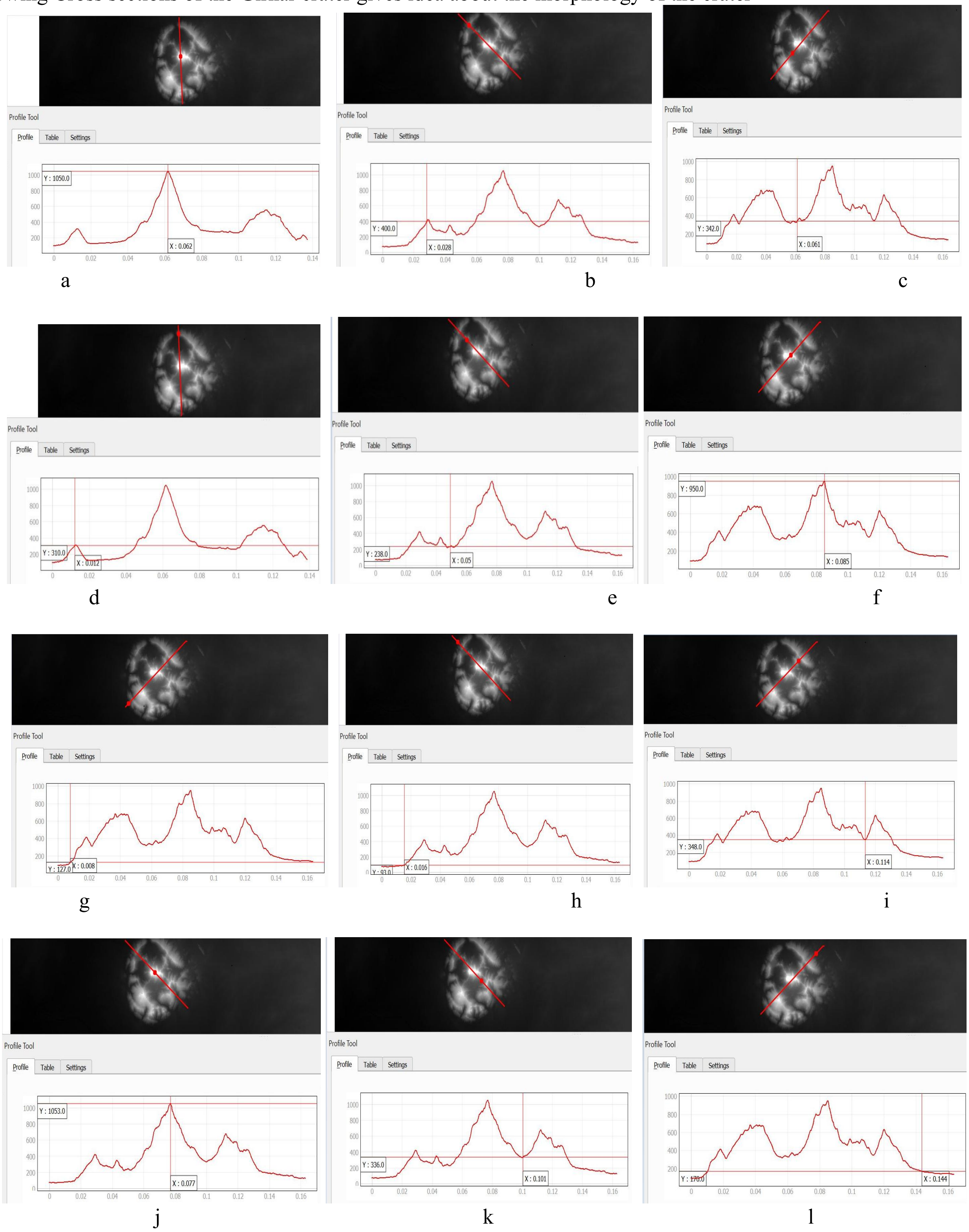


Fig.12. Cross Sections of the Girnar Crater (Author, 2025)

5. Limitations of the Study

This study has several limitations. First, the absence of fresh, unaltered samples restricts confirmation of definitive shock petrographic features that are essential for classifying a complex impact structure. Second, subsurface information is limited due to the unavailability of high-resolution geophysical or drilling data, which prevents detailed reconstruction of the crater's buried architecture. Third, prolonged weathering, tectonic modification and volcanic overprinting across the Girnar massif have altered primary mineralogical and geochemical signatures, complicating the distinction between impact-derived materials and later magmatic products. Fourth, spatial sampling was incomplete in inaccessible rim, breccia and ejecta zone sectors, potentially influencing representativeness. Finally, the absence of precise geochronological constraints limits the ability to establish the timing of the proposed impact event and its correlation with regional or global geological processes. Further Research: Conservation and management.

6. Further Research Work

Further work should integrate microstructural shock indicators, in-situ isotopic constraints, and deep geophysical imaging to resolve the competing volcanic and impact hypotheses. High-precision U–Pb and Ar–Ar geochronology is needed to temporally decouple impact-related melting from the Deccan volcanic sequence. Expanded trace-element systematics and noble-metal analyses will further test for projectile contributions. Region-scale gravity and magnetic modelling may reveal concealed crater architecture, while comparative analyses with other terrestrial hybrid structures will help refine diagnostic frameworks.

7. Conclusion:

The integrated geological, geomorphological and geochemical investigation collectively strengthen the Girnar structure as a probable complex impact-volcanic structure, its formation, evolution, and impact dynamics, geological process, multi ring morphology of crater, drainage morphology as well as the study reveals impact-volcanic origin of the crater. Geochemical datasets from XRF, ICP-MS, and SEM–EDS analyses reveal elevated siderophile elements, shock-related mineral microstructures, and localized melt-like compositions that are consistent with high-pressure impact processes. The presence of pseudotachylite-like veins, brecciated lithics, and mixed lithological assemblages further reinforces this hypothesis. While remnants of ancient magmatic activity are evident, the combined evidence points toward an impact-triggered or impact-modified volcanic system rather than a purely volcanic origin. Overall, the study provides the most comprehensive dataset to date supporting the reclassification of Girnar as a probable terrestrial complex impact structure in India, warranting further high-resolution geophysical and chronological investigations.

- **Acknowledgment**:

The author wish to gratefully acknowledge Dr. R.S. Chatterjee, Head and Senior Scientist, Geoscience Department, (IIRS,ISRO, Kalidas Road, Dehradun, Uttarakhand) for providing good support throughout research work. author also likes to acknowledge Mr. Amit Shrivastava. Assistant Scientist of IIRS, ISRO, Dehradun for their help in the lab work.

- **References**

1. **Ahnert, F., (1998)**. Introduction to Geomorphology. Arnold Publishers, London.
2. **Bell, F.G.(2007)** Engineering Geology. Elsevier, Amsterdam.
3. **Carporzen, L., Gilder, S.A., Zeh, A., (2012)** Evidence of shock metamorphism in impact structures. Earth and Planetary Science Letters 327–328, 61–70.
4. **C. Koebal & R.J Shook., (2007)** Impact Tectonics (pp-66-114) Springer
5. **Desai F.D. et. al., (2020):** Geomorphological and geological characteristics of the Girnar Crater, Saurashtra, Gujarat, India : A probable complex impact structure – journal of the Indian Society of Remote Sensing 48(2).257-269
6. **Deutsch, A., Koeberl, C., 2006.** Impact cratering: Basic concepts and mineralogical–geochemical signatures. Elements 2, 51–55.
7. **Ernstson, K., Fiebag, J., (1992).** Geophysical signatures of complex terrestrial impact structures. Tectonophysics 216, 313–324.
8. **French, B.M., (1998).** Traces of Catastrophe: A Handbook of Shock-Metamorphic Features in Terrestrial Impact Structures. Lunar and Planetary Institute, Houston.
9. **Grieve, R.A.F., Therriault, A.M., (2004).** Observations at terrestrial impact structures: Their utility in planetary studies. Meteoritics & Planetary Science 39, 199–216.
10. **Hartmann, W.K., (2019).** Terrestrial Impacts and the Cratering Record. Springer, Berlin.
11. **Ishiwatari, A., et al., (2005).** Geochemistry of impact melt rocks: An overview. Geochemical Journal 39, 1–11.
12. **J.K. Pati, W.U. Reimold, A. Greshake, R.T. Schhmitt, C.Koeber, P. Patil, K. Prakash (2015)** Pseudotachylitic breccia from the Dhala impact structure, north central India: Texture, mineralogy and geochemical characterization, Tectonophysics
13. **Jourdan, F., Renne, P.R., Reimold, W.U., (2009).** Dating of impact events: Methodology and application. Geochimica et Cosmochimica Acta 73, 479–497.
14. **Koeberl, C., (1994).** Geochemistry and origin of impact melt rocks. In: Dressler, B.O., Sharpton, V.L. (Eds.), Large Meteorite Impacts and Planetary Evolution. Geological Society of America Special Paper 293, 133–152.
15. **Liu, T., Schultz, P., (2010).** Impact-induced shock metamorphism and deformation structures. Journal of Structural Geology 32, 70–82.
16. **Mason, B., (1982)**. Meteorites. W.H. Freeman, San Francisco.
17. **Nolan, J., Powell, R., (2013)**. Indicators of hypervelocity impacts in terrestrial geology. Geological Journal 48, 134–150.

18. **Patel Sc. et. al. (2020):** Geomorphological evolution of the Girnar crater, Saurashtra, Gujarat, India: A complex impact structure journal of earth science 31(2), 147-156
19. **Patil S.C. et.al (2019):** Morhometric analysis of the Girnar crater, Saurastra, Gujarat, India: implications for impact cratering – Journal of Earth System Science 128 (4), 1-13
20. **Pilkington, M., Grieve, R.A.F., (1992).** Geophysical signatures of terrestrial impact craters. Reviews of Geophysics 30, 161–181.
21. **Reimold, W.U., Gibson, R.L., (2006).** The role of shock metamorphism in identifying impact structures. Annual Review of Earth and Planetary Sciences 34, 157–184.
22. **Sharma, R., Kumar, A., (2018).** Geochemical and petrological signatures of Deccan and Saurashtra igneous provinces. Journal of the Geological Society of India 92, 459–470.
23. **Singh P. et. al (2020):** Geomorphic and geological mapping of the Girnar crater, Saurashtra, Gujarat, India using remote sensing and GIS techniques – Journal of Applied Remote Sensing 14(2), 1-15
24. **Turtle, E., Pierazzo, E., (2003).** Numerical modeling of impact cratering processes. Annual Review of Earth and Planetary Sciences 31, 23–51.
25. **Willis, K., Mitchell, J., (2020).** Integrated geomorphic analysis of probable crater structures in India. Geomorphology 362, 107–122.
26. **Zolensky, M., et al.,(2014).** Mineralogical indicators of shock and impact processes. American Mineralogist 99, 21–30.
27. **Zheng, Y., Xiao, L., (2021)**. Shock deformation and high-pressure mineral phases in terrestrial impact structures: A review. Planetary and Space Science 203, 105276.