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Stratigraphic Synthesis of the Danau Rayo Geosite: Possible Impact Fragmentation

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ABSTRACT

Lake Rayo in West Sulawesi, Indonesia, has been proposed as a potential meteorite impact structure, yet direct evidence supporting this origin remains limited. This study aims to provide a preliminary stratigraphic and granulometric characterization of Lake Rayo's basin fill to clarify its genesis and support its geoheritage significance. Core sediment samples were collected from the basin floor and analyzed for grain size distribution, color (Munsell system), texture, and crack morphology using standard laboratory techniques. Seven stratigraphic intervals (BR1–BR7) were identified, showing clear vertical variations in granulometric parameters, sorting, and sediment color. Distinct fragmentation horizons, changes in color, and the occurrence of bedding cracks were interpreted as possible signatures of high-energy events, potentially associated with a meteorite impact. Comparative analysis with established impact structures, such as Lonar and Ries, revealed similar sedimentological features, supporting the impact hypothesis. These findings provide initial scientific evidence for the classification of Lake Rayo as an impact-related geoheritage site in Indonesia. The study also highlights the importance of integrating sedimentological data with future multidisciplinary research—such as geochemical and mineralogical shock analysis—to substantiate the impact origin more robustly. Overall, the results contribute valuable insights for geoheritage conservation, geoeducation, and the broader understanding of rare impact structures in Southeast Asia.

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1. INTRODUCTION

Lake Rayo, located in West Sulawesi, Indonesia, presents a distinct geomorphological feature characterized by its circular shape, closed drainage, and a well-defined basin morphology. Such features have led to the hypothesis that Lake Rayo may represent an ancient meteorite impact structure, a category of geoheritage with significant scientific and educational value. Vertical stratigraphic studies in analogous impact structures have shown that detailed sedimentological and granulometric analyses are critical for reconstructing basin evolution and assessing the origin of enigmatic landforms (French & Koeberl, 2010).

Vertical stratigraphic investigation is essential in potential impact basins because it can reveal evidence of high-energy depositional events, post-impact modification, and subsequent sedimentary infilling. These elements are commonly recorded through abrupt granulometric shifts, internal deformation, and discrete event layers in crater-lake successions. Comprehensive analysis of sedimentary sequences therefore provides insight into the dynamic history of such basins and supports geoheritage conservation by clarifying their formative mechanisms (Sari et al., 2024).

Morphological evidence alone is insufficient to confirm an impact origin for Lake Rayo, and direct geological indicators remain limited. Previous studies have primarily relied on remote sensing and morphometric analyses, which, while suggestive, are inadequate for definitive genetic interpretation. The absence of systematic coring and sedimentological profiling has maintained uncertainties about the processes responsible for basin formation (DM et al., 2025; Lenz et al., 2022).

A rigorous subsurface approach is required to resolve this problem. Detailed granulometric, textural, and vertical stratigraphic analyses provide a pathway to identify diagnostic features associated with impact events, including fragmentation horizons, anomalous bedding structures, and localized deformation (French & Koeberl, 2010). Such an approach enables the separation of impact-related deposits from products of non-impact geomorphic or sedimentary processes.

Global studies on confirmed impact craters demonstrate that their lacustrine fills preserve characteristic vertical successions. Impact structures such as Ries (Germany), Lonar (India), and Elgygytgyn (Russia) commonly exhibit abrupt changes in grain size, sorting, and sediment color, often coupled with deformational microstructures that reflect high-energy emplacement and rapid basin modification (Bodas & Sen, 2014; Kenkmann et al., 2014). At the Ries crater, systematic coring has revealed a transition from impact-derived breccias to quieter lacustrine infill identified through granulometric statistics (Catuneanu et al., 2006).

Comparable work at the Lonar crater shows that bedding cracks, color anomalies, and bimodal grain-size distributions may record catastrophic depositional pulses following crater excavation. These sedimentological fingerprints form a practical interpretive framework for recognizing impact-related processes even where diagnostic shock minerals are scarce (Chandran et al., 2023). The integration of stratigraphic description with granulometry and microtexture analysis is therefore a validated route for preliminary impact assessment (R. Chandran et al., 2022).

Multidisciplinary confirmation remains standard in impact science. Published crater-lake investigations emphasize that sedimentology provides the first-order reconstruction of basin evolution, while mineralogical and geochemical analyses are subsequently used to test for shock metamorphism and extraterrestrial signatures (French & Koeberl, 2010). This sequence of evidence building is particularly important for older or weathered structures where surface indicators may be muted.

Impact-related geoheritage studies in Indonesia are still rare, and most candidate sites have been evaluated largely from surface morphology and regional geophysics. Existing work on suspected structures has not yet produced a consistent sedimentological database comparable to that available for global analogues (Chen et al., 2024; Osinski et al., 2022). Consequently, Lake Rayo remains underexplored from a subsurface perspective.

A clear research gap persists in the absence of vertical stratigraphic and granulometric datasets for Lake Rayo. The lack of systematic core-based sediment profiling and the limited comparison to established impact-crater sedimentary models have impeded scientific validation of the basin's origin (Osinski et al., 2022). Filling this gap is necessary both for genetic interpretation and for credible geoheritage designation.

This study provides the first integrated stratigraphic and granulometric characterization of Lake Rayo's basin fill using sediment core analysis. The objective is to identify sedimentary, textural, and structural features that may serve as preliminary indicators of impact-related processes, thereby addressing a critical gap in Indonesia's geoheritage inventory. The novelty lies in applying a core-based, vertically resolved sedimentological approach guided by interpretive criteria from confirmed global impact basins (Stöffler et al., 2013).

The scope includes sediment coring, granulometric statistics, color and microtexture description, and interpretation of basin evolution within an impact-crater framework. The findings are intended to support Lake Rayo's geoheritage classification and to form a baseline for future confirmation through geochemical and shock-metamorphic investigations (Vasconcelos et al., 2019).

2. METHOD

2.1. Materials

The study area is located at Lake Rayo, West Sulawesi, Indonesia, situated at coordinates 1°02'23.5"S and 119°01'34.8"E. The lake occupies a closed, circular basin that is morphologically distinct from the surrounding Kasai Formation, which is dominated by fine-grained volcanic and sedimentary rocks. Lithological characterization of the basin and its environs was conducted based on field observations and core samples. The geological context, including the regional stratigraphy and lithology of the Kasai Formation, is summarized in Table 1. Core sampling points and key geomorphological features are illustrated in Figure 1.

Table 1. Sampling Coordinates

Sample Code	Coordinates
BR1	48 M 264201 E 9708187 N
BR2	48 M 264671 E 9708043 N
BR3	48 M 264675 E 9707652 N
BR4	48 M 264242 E 9707495 N
BR5	48 M 264003 E 9707775 N
BR6	48 M 264050 E 9707350 N
BR7	48 M 264772 E 9707529 N

The spatial distribution of core sampling points in relation to the circular basin morphology and surrounding geomorphological features is illustrated in Figure 1, together with documentation of the soil sampling procedure.

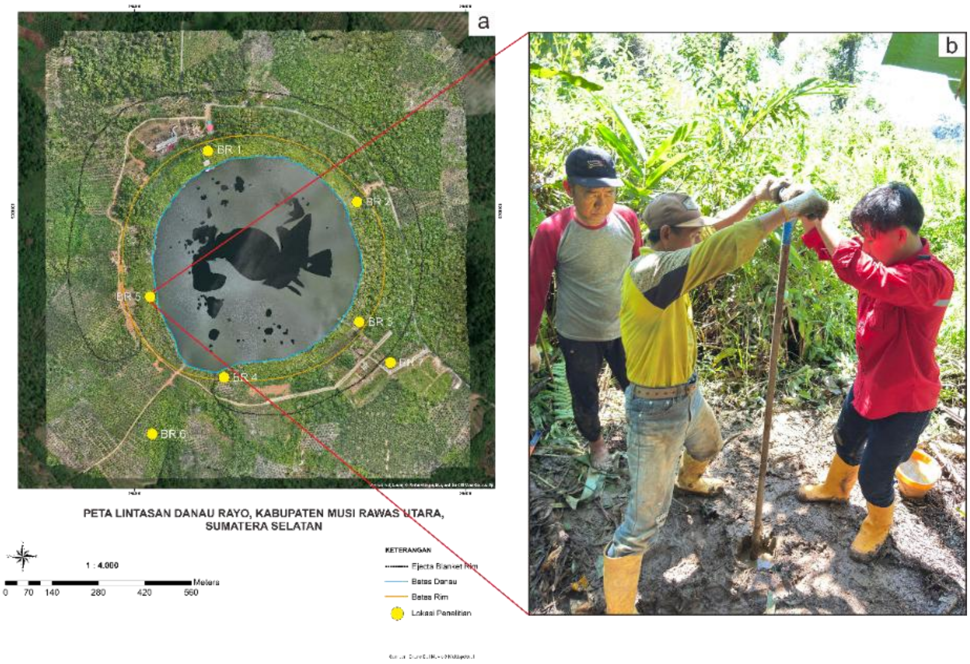

Figure 1. Map of the research location

2.2. Sample Preparation

Sediment cores collected from the lake floor were air-dried and subsequently oven-dried at 60°C for 24 hours to ensure moisture removal. Dried samples were gently disaggregated by hand to avoid grain breakage, followed by dry sieving using a nest of standard mesh sizes (2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.125 mm, 0.063 mm) for granulometric analysis. Each granulometric fraction was weighed to determine mass percentage. Representative subsamples were prepared for color and microtexture examination by mounting on glass slides and storing in sealed containers prior to analysis.

2.3. Field and Laboratory Procedures

Core recovery was accomplished using a manual percussion coring system equipped with PVC tubes (diameter 6.3 cm), capable of recovering undisturbed sediment sequences to depths of up to 60 cm below the lake bed. Cores were sealed, transported, and longitudinally split in the laboratory. Granulometric analyses were performed using a mechanical sieve shaker and digital balance. Grain morphology and texture were examined under a binocular microscope at magnifications up to 40×. Sediment color was assessed visually with the Munsell Soil Color Chart. Crack patterns and bedding features were documented photographically and described following field core splitting.

2.4. Parameters

Measured parameters included grain size distribution (mean diameter, sorting, skewness, kurtosis) calculated from sieve data using the Folk and Ward (1957) formulae. Sediment color was classified according to the Munsell system. Textural attributes, including roundness and sphericity, were assessed microscopically (Folk & Ward, 1957). Bedding cracks and structural discontinuities were categorized based on their orientation, continuity, and relationship to grain size or color changes. Interpretive criteria for fragmentation horizons and anomalous sedimentary layers were adopted from established studies (Nichols, 2009).

2.5. Data Processing and Visualization

Descriptive statistics for granulometric data were generated, including histograms and cumulative frequency curves for each stratigraphic interval. Sorting, skewness, and kurtosis classifications followed the Folk and Ward system. Unimodal and bimodal distributions were identified based on histogram morphology. All quantitative data analyses were performed using standard spreadsheet software (Microsoft Excel), with visualizations produced for comparison and interpretation of vertical trends.

3. RESULTS AND DISCUSSION

3.1. Stratigraphic Interval Description (BR1–BR7)

The seven stratigraphic columns (BR1–BR7) show systematic vertical variability in lithology, color, and grain size, dominated by sandstone intervals with subrounded grains, well-sorted textures, massive structures, closed packing, compact character, and non-carbonate composition. Detailed stratigraphic columns for BR1–BR3, BR4–BR5, and BR6–BR7 are presented in Figures 2–4.

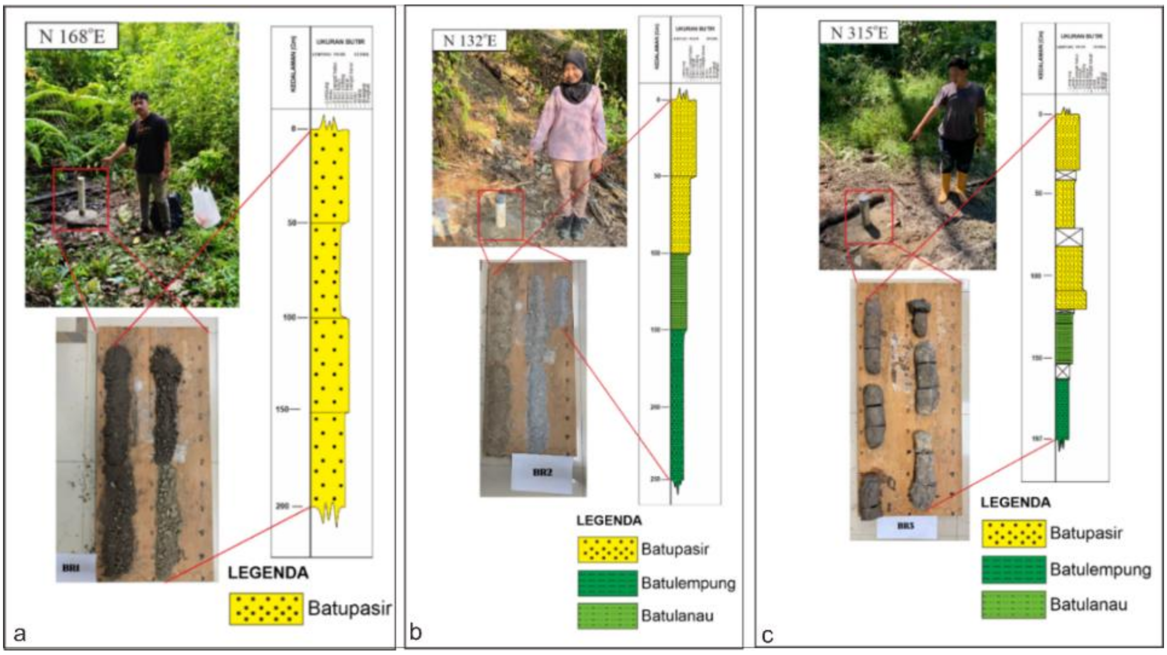

Figure 2. Stratigraphic Column; a). BR1; b). BR2; c). BR3

BR1 is characterized by sandstone-dominated deposits that record frequent vertical shifts in grain size within a compact and massive fabric. Sandstone dominates from 0–2 m, alternating between coarse and fine sand fractions. At depths of 0–0.5 m and 1–1.5 m, the sandstone is dark brown and composed of coarse sand (2–1/4 mm), whereas the 0.5–1 m interval consists of dark brown fine sand (1/16–1/4 mm). At 1.5–2 m, the sandstone becomes gray with medium sand (1/4–1/2 mm). Accessory minerals such as biotite, pyrite, and hornblende occur across multiple depth intervals.

BR2 records a clear fining-upward trend from sandstone to finer-grained lithologies, indicating a decrease in depositional energy. The upper section (0–1 m) consists of cream to cream–brownish sandstone, transitioning from medium sand (0–0.5 m) to very fine sand (0.5–1 m). This is followed by whitish-gray siltstone at 1–1.5 m (silt: 1/256–1/16 mm) and gray claystone from 1.5–2.5 m (clay: <1/256 mm). Biotite, pyrite, and hornblende fragments are present in several layers, particularly within the sandy intervals.

BR3 exhibits a stratigraphic succession in which sandstone remains dominant in the upper part before transitioning into siltstone and claystone at greater depths. Sandstone persists from 0–1.21 m with gray coloration and grain sizes ranging from fine to coarse sand. Fine sand dominates at 0–0.34 m and 0.4–0.7 m, while medium sand occurs at 0.8–1.1 m and coarse sand at 1.1–1.21 m. Below this, whitish-gray siltstone appears at 1.22–1.55 m, followed by whitish-gray claystone at 1.65–1.97 m. Biotite and pyrite fragments are common throughout the interval, with hornblende present in several sandy layers.

BR4 is distinguished by repeated alternations between siltstone and claystone, reflecting fluctuating depositional conditions with limited sandy input. Brownish-cream siltstone occurs at 0–0.3 m, followed by yellowish-cream claystone at 0.4–0.56 m and whitish-gray siltstone at 0.56–0.62 m. This alternation continues through the section, with claystone and siltstone interbedded between 0.79 and 1.82 m. A transition to sandstone is observed at 1.82–1.87 m, consisting of yellowish-brown very fine sand, which continues as fine sandstone from 2–2.2 m.

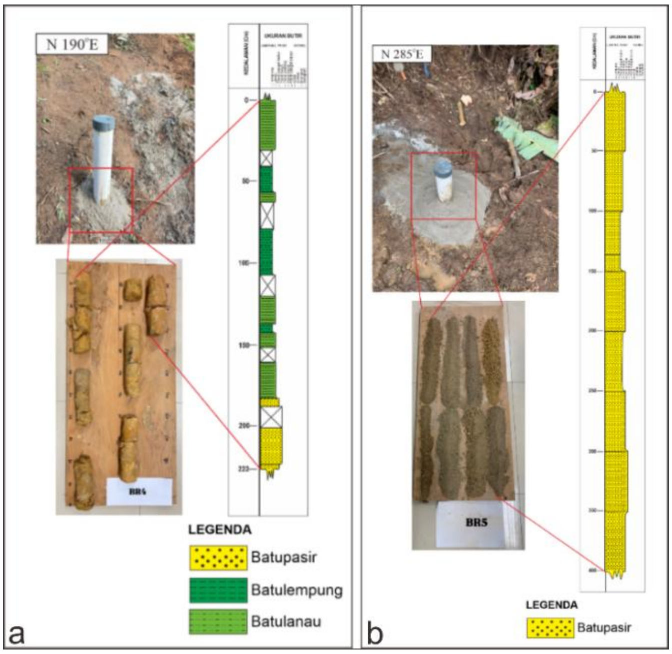

Figure 3. Stratigraphic Column; a). BR4; b). BR5

BR5 represents a thick sandstone-dominated sequence with pronounced vertical variability in both grain size and sediment color. Sandstone extends continuously from 0–4 m, beginning with brown medium sand at 0–0.5 m and brown fine sand at 0.5–1 m. Very fine yellowish-brown sandstone occurs at 1–1.5 m, followed by yellowish-gray medium sand at 1.5–2 m. Subsequent intervals alternate between fine and medium sand until coarser sandstone appears at 3–3.5 m, before returning to medium sand at 3.5–4 m. Biotite, pyrite, and hornblende fragments are distributed across several layers.

BR6 is characterized by sandstone deposits showing progressive changes in grain size and color with depth. Sandstone dominates from 0–2.5 m, starting with dark brown medium sand at 0–0.5 m and brown fine sand at 0.5–1 m. Coarser sandstone appears at 1–1.5 m and 1.5–2 m, with brownish-cream to cream coloration. The sequence terminates with gray fine sandstone at 2–2.5 m, indicating a shift toward finer-grained deposition.

BR7 records a sandstone-rich succession with relatively coarse grain sizes concentrated in the upper intervals. Sandstone dominates from 0–3 m, with dark brown coarse sand present at 0–0.5 m and 0.5–1 m. Very coarse sandstone (1–2 mm) occurs at 1–1.5 m, followed by brown fine sand at 1.5–2 m and brown medium sand at 2–3 m. This vertical arrangement highlights a gradual reduction in grain size with depth.

3.2. Cracks, Color Changes, and Fragmentation Indicators

Color variations across seven stratigraphic columns indicated depositional changes. BR1 transitions from dark to light gray at 1.5–2 m. BR2 changes from brown to gray at 1.5–2.2 m, BR3 at 2.5–3 m. BR4 shifts from yellow to yellowish-brown at 1.6–2.2 m. BR5 shows transitions: dark to light brown (1–2 m), grayish brown (2.5–3 m), yellowish brown (3–3.5 m), and dark brown (3.5–4 m). BR6 changes from dark to light brown (0.5–1.5 m), to grayish brown (1.5–2 m), and gray (2–2.5 m). BR7 shifts from dark to light brown at 1.5–2.6 m. While these patterns suggest fragmentation horizons, color changes alone cannot indicate impact-related fragmentation, likely reflecting groundwater fluctuations, redox processes, and mineralogical changes.

Radial and concentric fracture patterns around Lake Rayo rim were identified from field observations and DEM/satellite imagery analyses. However, fracture orientations lack quantitative documentation, and alternative origins remain viable. Crack geometry was interpreted using sedimentological criteria to distinguish desiccation-related polygonal cracks from linear structural cracks (Nichols, 2009).

3.3. Basin Evolution Interpretation: Impact, Modification, and Sedimentary Infill Phases

A three-stage depositional model is inferred from stratigraphic and granulometric trends, while acknowledging sedimentological indicators cannot confirm impact origin (French & Koeberl, 2010). The "impact-modification-infill" framework explains energy decay and sediment redistribution within the basin.

The impact phase may have formed Lake Rayo through a meteorite impact. Poorly sorted sediments and platykurtic kurtosis values show wide grain-size distributions, with mean sizes of 1–2 ϕ indicating medium- to fine-sand dominance from rapid energy decay. Similar features exist in the Ries and Nadir craters, but lacking diagnostic shock features or impactites makes this interpretation provisional (Fagel et al., 2024; Lim et al., 2025; Nicholson et al., 2024).

The modification phase involves post-formation stabilization, with weathering and wall-collapse becoming primary sediment sources. Fine-skewed grain distributions indicate lower depositional energy, while mesokurtic kurtosis suggests stable transport (Lee et al., 2023). Platykurtic kurtosis shows episodic coarser material influx, and poor sorting reflects mixing of fine weathering products and coarse detritus, with saltation as the main transport (Kasim et al., 2023).

The sedimentary infill phase reflects stable, low-energy lacustrine conditions with gradual basinward accumulation. Mean grain sizes of 1–2 ϕ, poor sorting, and fine-skewed distributions characterize basin deposits, while mesokurtic to leptokurtic kurtosis values indicate stable deposition along margins. Histogram patterns suggest depositional stability toward the basin center, though alternative depositional mechanisms require petrographic and geophysical verification.

3.4. Comparison with Other Impact Structures (Lonar, Elgygytgyn, Ries)

Lake Rayo shares sedimentological and granulometric characteristics with crater-lake successions, though lacking diagnostic confirmation. Rayo exhibits characteristics most similar to Lonar Crater, with poor sorting, fine-skewed distributions, and saltation processes in moderate-low energy deposition (Chandran et al., 2023). The stable mesokurtic kurtosis distribution resembles Elgygytgyn Crater, indicating calm sedimentary infill, while early platykurtic layers along the rim resemble Ries Crater's suevite units formed during initial crater formation (Table 2).

Table 2. Comparison with Other Impact Structures

Parameter	Rayo Lake (Indonesia)	Lonar Crater (India)	Elgygytgyn Crater (Russia)	Ries Crater (Germany)
Crater Diameter	~0,6 km	~1.8 km	~18 km	~24 km
Bedrock Lithology	Sedimentary and volcanic rocks	Basaltic (Deccan Traps)	Andesitic–rhyolitic	Carbonate sediments & granite
Grain Size (Mean)	1–2 φ (medium–fine sand)	1.5–2 φ (fine sand–silt)	>3 φ (silt–clay)	Mixed coarse–fine (suevite to fine sand)
Sorting	Poorly sorted	Poor–moderate sorting	Moderate–good in upper intervals	Poor in suevite, improving in resurge deposits
Skewness	Dominantly fine–very fine skewed, with one symmetrical layer in the basin	Fine skewed, indicating dominance of fine particles	Fine skewed–symmetrical, reflecting low stable energy	Coarse to fine skewed, reflecting variable depositional stages
Kurtosis	Mesokurtic dominant (4 basin layers), platykurtic (2 layers), leptokurtic (1 rim layer)	Mesokurtic to leptokurtic	Mesokurtic, indicating normal distribution	Platykurtic (suevite), mesokurtic–leptokurtic (resurge)
Dominant Transport Mechanism	Saltation, with minor suspension	Saltation and light suspension	Dominantly suspension	Traction and saltation
Depositional Energy	Decreasing from moderate to low (rim → basin)	Moderate–low, seasonally fluctuating	Low, stable, quiescent	High (impact phase), decreasing to moderate (resurge phase)
Depositional Environment	Closed crater lake	Basaltic crater lake with rim-derived input	Closed, stable crater lake	Open crater with resurge drainage system
Key Sedimentary Characteristics	Poor sorting, fine-grained dominance, saltation patterns	Fine sediments from basalt rim weathering	Fine-grained deposits, thin stable laminations	Poorly sorted suevite overlying fine-grained resurge deposits
Basin Evolution Type	Impact, modification, sedimentary infill phases	Impact, rapid infill	Long modification, slow infill	Impact, resurge, stabilization
Similarity to Rayo Lake	—	Moderate energy regime, dominant saltation, fine skewness	Low-energy, stable mesokurtic signature	Transition from high energy to stable phases, similar stratigraphic succession

3.5. Implications for the Geoheritage Classification of Rayo Lake and Potential Integration into Geoeducation and Geotourism

The sedimentological and geomorphological characteristics documented in this study support a provisional geoheritage framing for Lake Rayo as a candidate "impact crater lake," while acknowledging that confirmation requires diagnostic impact evidence. Accordingly, Lake Rayo is most appropriately regarded at this stage as a candidate "impact crater lake" geoheritage site with high potential scientific, educational, and conservation value. Nevertheless, this classification remains provisional pending confirmation by independent diagnostic evidence of impact origin, such as shock metamorphic features, impact-related geochemical anomalies, or geophysical signatures (Table 3).

Table 3. Implications for the Geoheritage Classification of Rayo Lake

Geoheritage Aspect	Description of Rayo Lake	Scientific Value & Global Comparisons	Value Classification
Scientific Value	Granulometric characteristics reveal the dominance of saltation, poor sorting, and fine-skewed distributions, indicating the impact of related processes and resurge deposition.	Comparable to Ries and Lonar Craters, both of which exhibit unsorted suevite layers associated with post-impact deposition.	High
Educational Value	Provides a direct example of the relationship between impact processes, weathering, and sedimentation within a crater lake system.	Similar to the utilization of Lonar Crater (India) as a natural laboratory for geological education.	High
Aesthetic Value	The circular rim morphology, calm lake water, and graded sediment layers produce strong visual contrasts.	Comparable to the Pingualuit Crater (Canada), known for its symmetrical morphology and distinctive water color.	Medium–High
Cultural & Social Value	The site has strong potential for geotourism development and for promoting narratives related to meteorite impacts.	Similar to the use of the Lonar Crater as both a scientific and spiritual tourism site.	Medium
Conservation Value	The closed-basin morphology and fine-grained sediment make the area susceptible to erosion and human disturbance; protection of the rim and core zone is necessary.	Consistent with conservation recommendations for the Ries and Elgygytgyn Craters.	High

Integration into geoeducation and geotourism can be directly supported by the stratigraphic, granulometric, and morphological findings. From a geoeducational perspective, Lake Rayo can function as a natural laboratory for teaching meteorite impact hypotheses, sedimentation dynamics, weathering, and depositional energy concepts. Granulometric trends (grain-size variation, poor sorting, fine-skewness tendencies, and the dominance of saltation) can be translated into field practicums and project-based learning modules for geology and geomorphology (Drinia et al., 2023; Spyrou et al., 2024).

From a geotourism perspective, the circular rim morphology and layered sediment textures provide strong potential for scientific tourism narratives and interpretive products, including information boards, educational trails, and field guides (Gupta et al., 2024). In this context, the study outcomes not only strengthen the scientific value of Lake Rayo but also provide an applied basis for conservation, public education, and sustainable local economic development linked to geoheritage and geotourism (Carrión-Mero et al., 2025).

4. CONCLUSIONS

This study presents a detailed stratigraphic and sedimentological investigation of Lake Rayo based on seven stratigraphic columns (BR1–BR7), providing new insight into the internal structure and depositional characteristics of the basin. The results demonstrate systematic vertical variations in lithology, grain size, and sediment color, with sandstone-dominated intervals interbedded with siltstone and claystone layers. These variations indicate fluctuating depositional energy and changing sedimentary conditions within a closed basin system.

The stratigraphic architecture reveals a general trend from coarser, poorly sorted sandstone units toward finer-grained deposits, punctuated by abrupt vertical changes in grain size and color. Such features are consistent with episodic high-energy inputs followed by periods of lower-energy sedimentation. When evaluated using an impact modification sedimentary infill framework, the observed stratigraphy supports a three-stage basin evolution model, although the sedimentological evidence alone is not sufficient to conclusively confirm an impact origin.

Comparison with well-documented impact structures such as Lonar, Elgygytgyn, and Ries shows that Lake Rayo shares several granulometric and depositional characteristics with crater-lake systems, particularly in terms of poor sorting, fine-skewed distributions, and dominant saltation processes. Based on these findings, Lake Rayo can be regarded as a candidate impact-related geoheritage site with high scientific, educational, and geotourism potential. However, definitive validation of an impact origin requires further multidisciplinary investigations, including shock metamorphic, geochemical, and geophysical analyses.

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