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The Impact of Restoration Work and Climate Change on the State of the Barakoni Cathedral

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Summary. The Barakoni Cathedral, built in 1753 in the Racha region of Georgia, stands as a distinguished monument of Georgian ecclesiastical architecture. Recent observations have identified chemical and biological deterioration on its walls, including surface greening and cracking. This paper analyzes how restoration interventions, particularly, the replacement of the original roofing with copper and ongoing climate change (e.g., increased humidity, rain, and thermal stress) contribute to the degradation of the building stone. Emphasis is placed on the material's mineralogical composition and associated chemical weathering mechanisms to offer science-based recommendations for conservation.

Keywords: Barakoni, Heritage, Erosion, Climate Change, Negative Impact

Introduction. The Barakoni Cathedral of the Mother of God, commissioned in 1753 by Duke Rostom of Racha, is a distinguished representation of Georgia's late medieval ecclesiastical architecture. Located in the village of Tsesi, the cathedral is uniquely situated on a steep rocky promontory overlooking the confluence of the Rioni and Lukhuni rivers. This setting, while visually striking, subjects the structure to a range of natural and anthropogenic stressors including hydrological exposure, seismic activity, and fluctuating microclimatic conditions.

Constructed from locally sourced, finely hewn stone blocks, the cathedral features a domed cruciform design enriched with intricate decorative reliefs.

The cathedral's location in a geomorphologically active zone subjects it to frequent humidity fluctuations, capillary water movement, and periodic freeze-thaw events. These processes promote salt crystallization and microcracking within the stone matrix, which are further amplified by the structure's exposure to prevailing winds and seasonal rainfall. Barakoni also sustained minor structural damage during the 1991 Racha earthquake, which was followed by a series of rapid and, in some cases, ecologically insensitive restoration efforts. For example, the replacement of the original stone-compatible roofing with copper sheets—although intended to improve weather resistance has introduced new chemical dynamics.

Furthermore, incompatible modern mortars were used during the restoration work, resulting in differential weathering, where the original and restored materials deteriorate at different rates. These mismatches have accelerated mechanical stresses at stone-mortar interfaces and caused further microstructural deterioration.

In ecological terms, the Barakoni Cathedral exists within a sensitive transitional zone between riverine and montane ecosystems. Microclimatic shifts due to climate change—such as increased rainfall intensity, humidity variation, and temperature extremes—are now actively influencing the biodeterioration of the façade through lichens, mosses, and microbial biofilms that release organic acids capable of degrading carbonate stone.

To preserve the monument within this dynamic natural environment, it is critical that future conservation interventions adopt a material-science-informed, eco-sensitive approach. This includes the use of compatible mortars, non-invasive biological cleaning, breathable surface treatments, and hydrological engineering to prevent water retention. Without such scientifically guided action, both the cultural and ecological integrity of the Barakoni Cathedral may continue to erode.

Aim and Objectivs. Our research began in January 2024. The research is aimed at development of a methodology for the mechanisms of long-term protection of historical and architectural heritage in some regions of Georgia in the face of climate change. Barakoni Cathedral, as one of the monuments under investigation, serves as a case study representative of rural heritage sites subjected to natural forces such as precipitation, temperature fluctuations, freeze–thaw cycles, and slope instability, as well as post-restoration impacts such as the introduction of copper roofing. These factors have led to observable damage patterns including surface erosion, bio-colonization, salt efflorescence, and structural microcracking.

The objectives of this study is to evaluate the impact of meteorological parameters and restoration interventions—particularly the installation of a copper roof on the material integrity of Barakoni Cathedral. To achieve this, the study integrates mineralogical characterization of building materials with on-site visual inspection and historical meteorological data analysis.

The methodology includes:

- X-ray Powder Diffraction (XRD): Employed to determine the mineralogical composition of building stone samples taken from visibly deteriorated upper wall sections;
- Visual assessment: Used to correlate surface decay patterns with structural modifications and environmental exposure;
- Meteorological data assessment: Performed to understand the influence of weather variability on decay mechanisms.

XRD analysis was conducted in 2024, using Cu Kα_1 radiation (λ = 1.5406 Å). Samples were carefully collected to avoid damage to the historic fabric and to maintain compliance with conservation ethics.

Experimental Results and Discussion. The aim of our research was to evaluate the influence of meteorological factors and the recently conducted roofing interventions on the structural integrity of the Barakoni Cathedral. Particular attention was paid to the upper wall sections, where visible deterioration has become evident following restoration activities.

As a first step, a X-ray powder diffraction (XRD) analysis was performed on samples collected from the cathedral's building stone. This non-destructive analytical technique enabled the identification of the mineralogical composition of the materials. The resulting diffractogram revealed pronounced peaks corresponding to the crystalline phases of calcite ($CaCO_3$) and dolomite ($(Ca,Mg)CO_3$), which are the primary constituents of the stone (Fig.1).

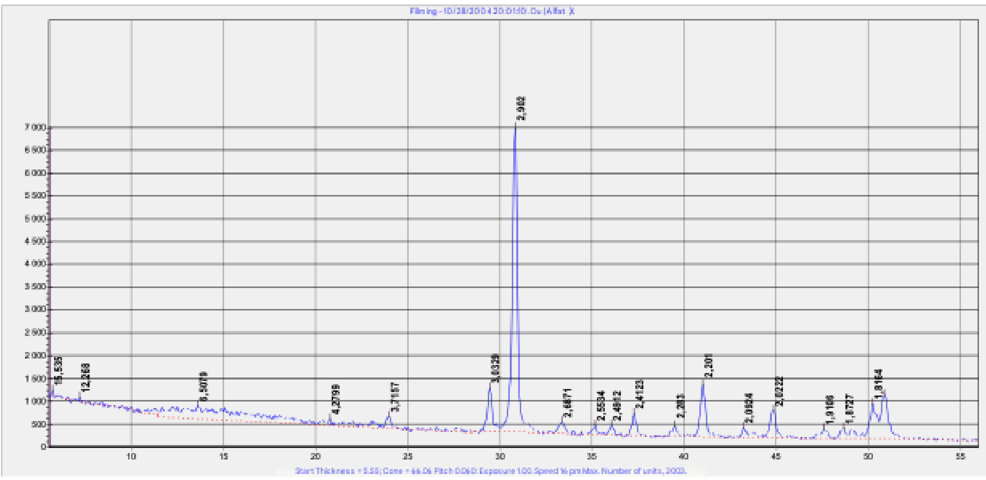

Figure 1. X-ray diffraction (XRD) pattern of the stone sample from Barakoni Cathedral obtained using Cu Kα_1 radiation (λ = 1.5406 Å), 2024.

The most intense diffraction peak, located at approximately 2θ = 29.02°, is characteristic of calcite, confirming its dominance in the stone matrix. Additional peaks at 2θ = 30.29°, 2θ = 50.79°, and 2θ = 12.86° support the presence of dolomite and minor accessory phases, indicating a mixed carbonate composition typical of local sedimentary rock formations.

The carbonate minerals are well-documented for their high porosity and reactivity with acidic environments, making them particularly vulnerable to chemical weathering. Calcite, being the thermodynamically less stable phase, readily undergoes dissolution when exposed to slightly acidic precipitation (pH < 5.6), particularly in the presence of sulfuric or nitric acids products of anthropogenic air pollution (Doehne & Price, 2010, Steiger M. & Charola A. E., 2011).

Furthermore, dolomite's relative resistance to dissolution is offset by its susceptibility to mechanical stress and salt crystallization in fluctuating humidity environments (Steiger M. & Charola A. E., 2011). The dual presence of calcite and dolomite in the Barakoni stone indicates a material that is both chemically reactive and mechanically vulnerable, particularly in the context of climate change-induced variability in precipitation and temperature, which exacerbates crystallization pressure and microcrack propagation (Smith et al., 2004).

Importantly, the mineralogical composition of the stone significantly influences its long-term interaction with restoration materials, particularly in the presence of metal components exposed to environmental conditions.
In the case of the Barakoni Cathedral, the copper roof, which was installed in 2021 (inaccurate information) - though effective in protecting the interior from direct precipitation—may have introduced new deterioration pathways for the underlying carbonate stone. Under the influence of rainwater and atmospheric CO_2, copper undergoes oxidative weathering, releasing Cu^{2+} ions, which react in the presence of moisture and carbonate substrates to form basic copper salts such as copper hydroxide [$Cu(OH)_2$], malachite [$Cu_2CO_3(OH)_2$], or azurite [$Cu_3(CO_3)_2(OH)_2$] (chemical reactions 1-5) (Rodriguez-Navarro & Sebastian, 1996).

1. Copper oxidation (under atmospheric conditions):
$2Cu\ (s) + O_2\ (g) + 2H_2O\ (l) \rightarrow 2Cu(OH)_2\ (s)$

2. Malachite formation (reaction with carbon dioxide):
$2Cu(OH)_2\ (s) + CO_2\ (g) \rightarrow Cu_2CO_3(OH)_2\ (s) + H_2O\ (l)$

3. Azurite formation:
$3Cu(OH)_2\ (s) + 2CO_2\ (g) \rightarrow Cu_3(CO_3)_2(OH)_2\ (s) + 2H_2O\ (l)$

4. Calcite decomposition in acidic environment:
$CaCO_3\ (s) + 2H^+\ (aq) \rightarrow Ca^{2+}\ (aq) + CO_2\ (g) + H_2O\ (l)$

5. Dolomite decomposition in acidic environment:
$(Ca,Mg)CO_3\ (s) + 2H^+\ (aq) \rightarrow Ca^{2+}\ (aq) + Mg^{2+}\ (aq) + CO_2\ (g) + H_2O\ (l)$

These secondary copper compounds can accumulate on stone surfaces, forming greenish patinas that not only alter the aesthetic appearance but also reduce the stone's permeability, trapping moisture and promoting subflorescence of salts. Additionally, the slightly acidic nature of copper runoff, especially in polluted atmospheres where frequent rain is prevalent, enhances the dissolution of calcite and dolomite phases, accelerating surface recession and granular disintegration. This is particularly critical in stones with high porosity or pre-existing microcracks, where capillary absorption facilitates deeper infiltration of aggressive agents.

Furthermore, galvanic interactions between copper elements and embedded iron or steel (often used in anchors or structural supports) can lead to electrochemical corrosion, indirectly affecting adjacent stone materials through the formation of expansive corrosion products (Benavente et al., 2007). These combined effects underline the importance of selecting chemically compatible restoration materials that account for the geochemical sensitivity of the host stone.

The importance of this study is further heightened by the ongoing climatic changes documented in the Ambrolauri region, where Barakoni Cathedral is located. Recent meteorological data reveal a consistent rise in the annual average temperature by 0.3°C per decade, suggesting intensified thermal stress on building materials and accelerated physical weathering. This temperature increase, when combined with freeze–thaw cycles typical for mountainous regions, enhances the risk of microcracking and exfoliation of stone surfaces (Fig.2).

Furthermore, precipitation variability with fluctuations of up to ±300 mm annually indicates growing instability in the region's water supply. Such irregularities affect both surface runoff and subsurface moisture dynamics, leading to non-uniform moisture exposure of exterior walls. This enhances erosion, salt transport, and bio-colonization, especially in areas where drainage systems are inadequate or surface protection has been compromised (Fig.2).

Wind speed increases, averaging an additional 0.200.5 m/s over recent decades, contribute to higher risk of mechanical erosion through abrasive particles and enhanced drying effects. These impacts are particularly noticeable in elevated locations such as the Nikortsminda area, where wind exposure is more severe and direct .

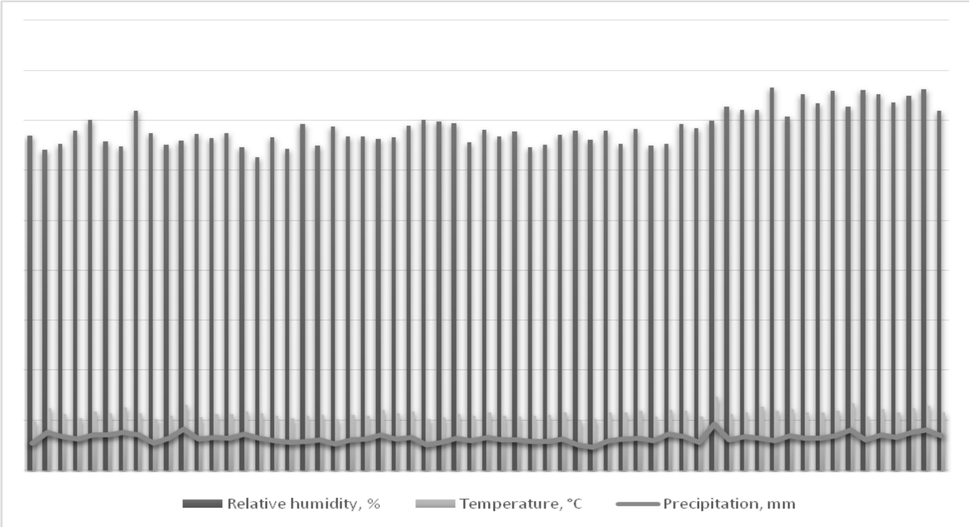

Figure 2. Some meteprological parameters (Ambrolauri weather-station data 1956-2016)

An important anthropogenic factor contributing to the alteration of meteorological and microclimatic conditions in the Racha-Lechkhumi region is the Shaori Reservoir, which was put into operation in 1954 (Kandelaki N., 2020). The creation of this artificial water body led to notable changes in local meteorological parameters and contributed to the formation of a distinct microclimate in the surrounding area, including zones near the Barakoni Cathedral.

The presence of a large water surface affects air humidity, temperature fluctuations, wind circulation, and precipitation patterns. After the reservoir's commissioning, long-term observations indicate:

- Increased relative humidity, particularly during the warmer months, due to constant evaporation from the reservoir surface.
- More frequent fog formation and cloud cover in adjacent areas, which reduces solar radiation exposure on monument surfaces, potentially decreasing thermal stress, but at the same time increasing moisture retention, which fosters material degradation through biological growth and salt crystallization.
- Local wind pattern alterations, where lake–land breeze cycles formed, modifying the dominant wind direction and speed in nearby valleys.
- Slight temperature moderation, especially in nighttime values, due to the thermal inertia of the water body.

These microclimatic shifts have negative impact on the state of cultural heritage monuments like Barakoni. Increased moisture levels and altered airflow enhance physical, chemical, and biological weathering processes on stone and mortar.

Conclusion. The results of this study underscore the complex interplay between restoration interventions and evolving climatic conditions in shaping the long-term stability of the Barakoni Cathedral. The XRD analysis confirmed that the cathedral's building stone is primarily composed of calcite and dolomite—minerals known for their chemical reactivity and mechanical vulnerability under acidic and fluctuating environmental conditions. Restoration efforts, particularly the installation of copper roofing, have introduced new chemical interactions leading to the formation of copper-derived patinas and increased moisture retention. These processes accelerate both chemical and physical weathering.

Additionally, climate change has intensified stressors such as thermal expansion, freeze–thaw cycles, increased precipitation, and biological colonization, all of which compound the rate of deterioration. The rising average temperatures, precipitation variability, and wind intensification in the Racha region highlight the need for adaptive and scientifically grounded conservation strategies.

To mitigate further degradation, it is essential to adopt restoration materials and methods that are mineralogically and chemically compatible with the original stone. This includes avoiding metals that can promote secondary reactions, using breathable and reversible treatments, and implementing environmental control measures such as improved drainage and vegetative buffers.

Overall, the Barakoni Cathedral serves as a critical case study illustrating the need for interdisciplinary approaches combining material science, environmental monitoring, and architectural conservation to preserve Georgia's historic monuments under changing climatic and anthropogenic pressures.

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სარესტავრაციო სამუშაოებისა და კლიმატის ცვლილების გავლენა ბარაკონის ტაძრის მდგომარეობაზე/ ნათელა ძებისაშვილი, ნუგზარი ბუაჩიძე, დარეჯან დუღაშვილი, ნოდარ ფოფორაძე, ვერა მაისურაძე, ლელა ნინოშვილი/სტუ-ის ჰმი-ის შრომათა კრებული-2025.-ტ.136.-გვ.128-132. - ინგ., რეზ. ინგლ., ქართ., რუს.

ბარაკონის ტაძარი, რომელიც 1753 წელს აშენდა რაჭის რეგიონში, წარმოადგენს ქართული საეკლესიო არქიტექტურის გამორჩეულ ძეგლს. ბოლო პერიოდში ჩატარებულმა დაკვირვებებმა ტაძრის კედლებზე ქიმიური და ბიოლოგიური დეგრადაციის ნიშნები გამოავლინა, მათ შორის ზედაპირის გამწვანება და ბზარების წარმოქმნა. ნაშრომი აანალიზებს, თუ როგორ განაპირობებს შენობის ქვის დეგრადაციას რესტავრაციის პროცესები — განსაკუთრებით თავდაპირველი გადახურვის შეცვლა სპილენძის სახურავით — და კლიმატური ცვლილებები, როგორიცაა ტენიანობის ზრდა, უხვი ატმოსფერული ნალექი და თერმული სტრესი. განსაკუთრებული ყურადღება ეთმობა სამშენებლო ქვის მინერალურ შემადგენლობას და მასთან დაკავშირებულ ქიმიური დაშლის მექანიზმებს, რათა შემუშავდეს კონსერვაციის სამეცნიერო რეკომენდაციები.

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Собор Баракони, построенный в 1753 году в регионе Рача, является выдающимся памятником грузинской церковной архитектуры. Недавние наблюдения выявили химическое и биологическое разрушение его стен, включая позеленение поверхности и появление трещин. В данной работе анализируется, как реставрационные вмешательства — особенно замена первоначальной кровли на медную — и продолжающиеся климатические изменения (повышенная влажность, обильные атмосферные осадки и термический стресс) способствуют деградации строительного камня. Особое внимание уделяется минеральному составу материала и связанным с ним механизмам химического выветривания с целью разработки научно обоснованных рекомендаций по сохранению памятника архитектуры.