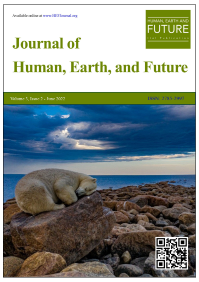
HUMAN, EARTH AND FUTURE
Ital Publication

ISSN: 2785-2997

Available online at www.HEFJournal.org

Journal of
Human, Earth, and Future

Vol. 3, No. 2, June, 2022



Non-Destructive Analysis to Investigate the Stone Alterations at a UNESCO World Heritage Site

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Received 11 March 2022; Revised 18 May 2022; Accepted 25 May 2022; Published 01 June 2022

Abstract

This study concerns the eleven monolithic churches in Lalibela, in northeastern Ethiopia, a UNESCO World Heritage Site and currently the main pilgrimage site in Ethiopia. In 2019, on the initiative of Prime Minister, the French authorities proposed their support in the management on the site of the churches. To do so, the French Development Agency (AFD), in collaboration with the Ministry of Europe and Foreign Affairs and with the support of the Ministry of Culture, granted a feasibility study to examine ways of restoring, conserving, and developing the rock-hewn churches. The objective of the feasibility study conducted was to produce the preliminary technical diagnostics required for the preparation of the comprehensive project to restore, conserve, and develop the site. In order to propose a protection and conservation solution, diagnostics and analysis of the pathology of the rocks were made during two campaigns in November 2019 and November 2020. The rock pathology teams implemented non-destructive and minimally invasive analysis. The complementary methods acquire data from the rock surface and the different forms of differential alteration of the scoriaceous basalt. The objective is to characterize, through comparative analyses, the impact of a protective shelter on the alteration kinetics of the rock. The analysis, coupled with on-site observations, suggests that deterioration linked to liquid water and the persistence of a state of high water content is more damaging than the deterioration risk linked to salt crystallization. As water is the key factor in the very harmful alteration for the conservation of scoriaceous basalt as a heritage material in humid natural environments, it seems useful to fully cover the churches.

Keywords: Lalibela Churches; Non-Destructive Analysis; Scoriaceous Basalt; Water Content.

1. Introduction

Lalibela is located 600 km north of Addis Ababa, in northern Ethiopia, at an altitude of 2500 m. The Lalibela UNESCO World Heritage Site is composed of eleven medieval monolithic churches carved out of rock. Their construction is attributed to King Lalibela in the 12th century to be a "*New Jerusalem*" [1]. The churches are still used today for religious practices and ceremonies, and large crowds of believers and pilgrims gather at the site during major religious events, mingling with an increasing flow of tourists [2].

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doi http://dx.doi.org/10. 28991/HEF-2022-03-02-01

There are two main groups of churches, located on both sides of the Jordan River: South side, Biete Amanuel, Biete Qeddus Mercoreus, Biete Abba Libanos, Biete Gabriel Raphael, and Biete Lehem; and the North side: Biete Medhani Alem (the largest monolithic church in the world), Biete Mariam, Biete Maskal, Biete Denagel, and Biete Golgotha Mikael. The last, and probably the most iconic one, Biete Ghiorgis, is isolated from the others and has a remarkable cruciform plan. The churches were not constructed in a traditional way but rather were hewn from the living rock of monolithic blocks. These blocks were further chiselled out, forming doors, windows, columns, various floors, roofs, etc. This gigantic work was further complemented with an extensive system of drainage ditches, trenches, and ceremonial passages, some with openings to hermit caves and catacombs [3-5].

The scoriaceous basalt flows in which the churches are carved correspond, on a geological scale, to various chemical and mineralogical compositions. On a metric to decametric scale, these differences are clearly visible. They are characterized by different colors (orange to purple ton), decay and alteration states. Such varied textural properties are linked with the initial chemical composition of the basalt effusion. Intensity of the rock transformations at its subsurface is assumed to play the key role in order to explain the various degradation states observed nowadays, especially concerning cracks development [6-8]. In order to understand the physical behavior of scoriaceous basalt samples, it is necessary to identify the impact of the main weathering factors on these rocks. Variations in temperature and humidity are considered here as key parameters of the rock's resistance to atmospheric agents, especially as some churches are protected from heavy rain [9-10]. Climatic parameters, including temperature and humidity, are the main stresses, and variations are important in order to characterize their influence on rock behavior. This is the reason why microclimatic monitoring took place in October 2019 to document these parameters. Twelve temperature (T) and relative humidity (RH) sensors have been placed in strategic locations [11].

In order to evaluate the sensitivity of the rock to meteorological decay and weathering, several additional methodologies were implemented. The selected techniques are focused on scientific practices well known in the field of stone conservation and conservation of natural outcrops [11]. Rocks are subjected to continuous decay, water runoff, biological development, granular disintegration and particles impact carried by winds which lead to significant rock texture change.

Because rainwater is the main media liable for producing irreversible alteration, its influence is characterized by the expression of washing, dissolution or gullying according to the potential energy of water flows. These leached rock surfaces are therefore naturally modified and induce the evolution of the surface macro-roughness. Such modification of surface texture is usually expressed by a change in rock microstructure and the porosity, and, consequently, the surface permeability [12]. As the current porosity characterization techniques are all destructive, it is an interesting challenge to assess the impact of these solution transfers and therefore the rock ability to be affected by fluids.

This study analyses the results obtained in a comparative approach between (i) the area exposed to water transfer and rainwater percolation and (ii) the area currently protected by a shelter.

2. Materials and Methods

2.1. Microclimatic Monitoring

Twelve probes to measure the temperature (T), the relative humidity (RH) and the dew point (DP) were located in Lalibela churches, majority of them outside, as seen on Figure 1. The measurements took place from October the 24th 2019 to September the 4th 2020, with four measurements per day at 00:00, 06:00, 12:00 and 18:00.

- Beta Medhane Alem: S1, S2, S4 on the facade, respectively East (E), North (N) and West (W), S3 inside North;
- Beta Maryam: S5 on the W façade;
- Beta Gabriel Rufael: S6 inside and S7 on the W façade;
- Beta Amanuel : S8 and S9 on the facade, E and W respectively, S10 inside the church;
- Beta Libanos: S11 facade E, S12 inside the church.
- For the purpose of this study, the focus will be given on the comparison between Beta Maryam (S5) and Beta Libanos (S11).

The probes used are PROGES brand sensors with an external shape similar to a small standalone button (2 cm in diameter and 5 mm high in size). The humidity is measured via a capacitive probe with a resolution 0.1% RH (relative humidity) and 0.1°C in temperature. After calibration in the laboratory to ensure the stability and accuracy of the measurements with time, scan step was set at four measurements per day. Figure 1, the measurement uncertainties are not shown (with the error bar) to improve their readability, but it is taken into account in the analysis of the data.

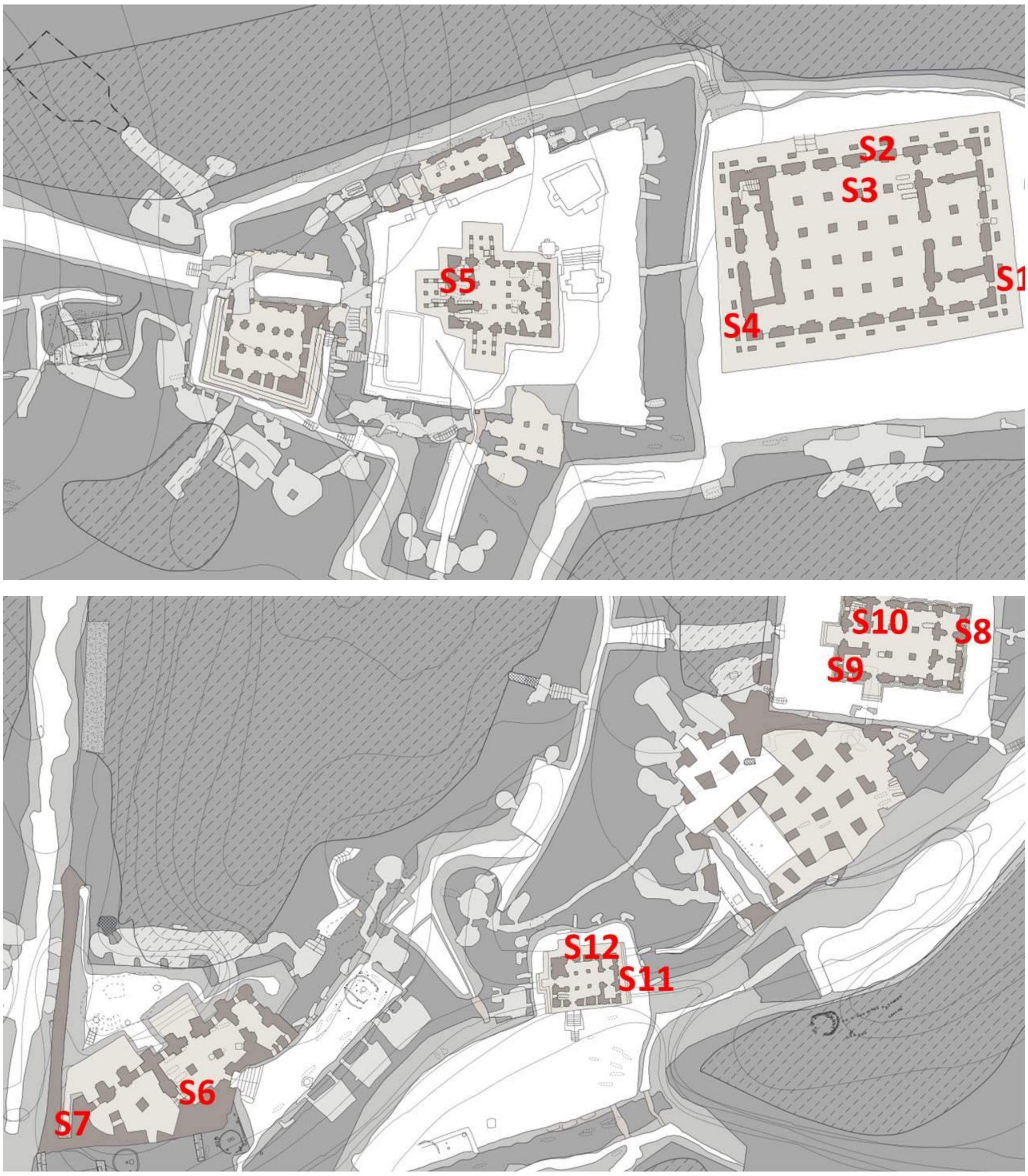

Figure 1. Implementation of the probes inside and outside of the churches

2.2. Non-destructive Evaluation Of The Rock with/without Shelters

Selection of the Tested-Zones

The selected test zone corresponds to the counter-scarp west wall of beta Maryam (Figure 2) and more precisely the two vertical profiles: one to the south part (profile 1) and the other to the north part (profile 2). These two wall profiles have the same orientation (West) and a similar height of around 4 to 5 meters. The main difference is due to the fact that:

- *Zone 1* is exposed to rains;
- *Zone 2* is not exposed and protected by the shelter.

Test-surface 1, not protected by the shelter, is located at 2.40 m beyond the southwest corner while test-surface 2, protected, is located at the other side of the same wall, at 2.50 m from the northwest corner. These two areas represent visually comparable zones but different surface states. The wall of zone 1 is 4.10 m in height while the wall of zone 2 is 5.30 m in height from the top of the rock outcrop. Different investigations have been performed on these surfaces.

Roughness Evaluation of the Walls

At a first glance, the main difference between the rocks of Lalibela covered or uncovered by the shelter is the following:

- Colour: greenish for uncovered parts due to the presence of microorganisms, such as algae (black appearance) and lichen; and redish for the covered ones, as visible on Figure 2,

- Morphology: very rough for the uncovered area, smoother for covered parts,
- Humidity: appears humid in the uncovered areas and dryer in the covered parts.

In order to highlight the differences between those two parts, the decision was taken to focus on Beta Maryam, on the western area of the of the church's courtyard.

Figure 2. Location of the tested-zones, View to the East.

The measurements were performed using a 3D scan, GoScan by Creaform. This system allows to capture the form of the object by using the deformation of a grid projected on the surface of the object to capture. The deformation of this grid is then recorded by a camera, and simultaneous recording of the surface by 3-colour cameras allow to make photogrammetry. As a result, the system can make analysis at a meter scale with a maximum resolution of 200 µm.

The standard ISO 2578 [13] describes the techniques to measure roughness and evaluates the amount of parameters to be around 100 to describe it. The most common parameter chosen to characterize the roughness of a surface is S_a, parameter which corresponds more or less to the average roughness. In fact, the physical meaning of S_a is ubiquitous, because it is the average of the absolute value of height. It means that S_a does not take into account if the roughness is a peak or a valley.

Table 1. Definition of the chosen parameters to characterize the roughness

Parameters	Definition
S_a	The Arithmetic Mean Of The Absolute Values Of The Roughness Profile Ordinates
S_q	The Root Mean Square Average Of S_a
S_v	The Maximum Valley Depth Of The Roughness Profile
S_p	The Maximum Peak Height Of The Roughness Profile

The calculation of the different parameters is made after the definition of a baseline, or base-surface, which is represented by the mean line/surface, i.e. the sum of the heights to that line/surface is null

Transient Gas Permeability

In the field of stone or rock conservation, air permeability K is a major issue because permeability affects "*breathing*" of porous media as well as hydric equilibrium of rock with environmental conditions and durability. In the present case study, Darcy's permeability is mainly due to the pores' size connectivity and surface roughness. As a result, permeability measurement is often used to evaluate the change in rock properties during alteration processes as well as for conservation state diagnosis. During the last decades, the usual permeameter for gas-driven measurements use the Hassler cell and require cylindrical core samples generally tested under a steady-state fluid flow, especially for high pressure experiments.

At Lalibela site, an innovative non-destructive method to perform on-site measurements was tested in order to limit sampling and avoid the damage of valuable rock heritage. Main developments happened not only on probe permeameter devices that work on a steady flow but also on a transient regime [14]. Since handheld mini-permeameter can be used to detect small variations at a centimetre-scale, relevance of measurements has been studied directly by contact with the stone surface. On the two wall-zones, the pulse-decay method is applied because it is easier to control the fluid transfer by applying a vacuum to the stone rather than injecting a pressurized gas volume to minimize air leakage at the stone interface [15].

Permeability is determined by applying a fixed depressurized volume of air against the porous stone surface and by measuring the resulting flux versus time. The methodology allows also validating the application of Darcy's law, and therefore the measurement, by checking the Reynolds number. The tested portable permeameter is the commercial device TinyPerm II (New England Research Company, USA). It was used in combination with the Cydar™ software (Cydarex Company, F) in order to calculate the air permeability change versus the height of the measurements on the wall. The investigated volume of rock taken into account for the calculation of the permeability is about 10 mm in depth into the wall.

3. Results

3.1. Microclimatic Monitoring

Condensation

The analysis of the dew point (DP) allows evaluating the possibility of condensation. If the temperature is higher than the dew point, condensation could happen at the surface of the rock. For the 9 areas, the DP is directly calculated from the Magnus equation. A comparison between the temperature measured on each point and the DP is then done. For the whole set of probes, only two present such situations, in Beta Maryam (S5) and Beta Libanos (S11), as seen on Figure 3.

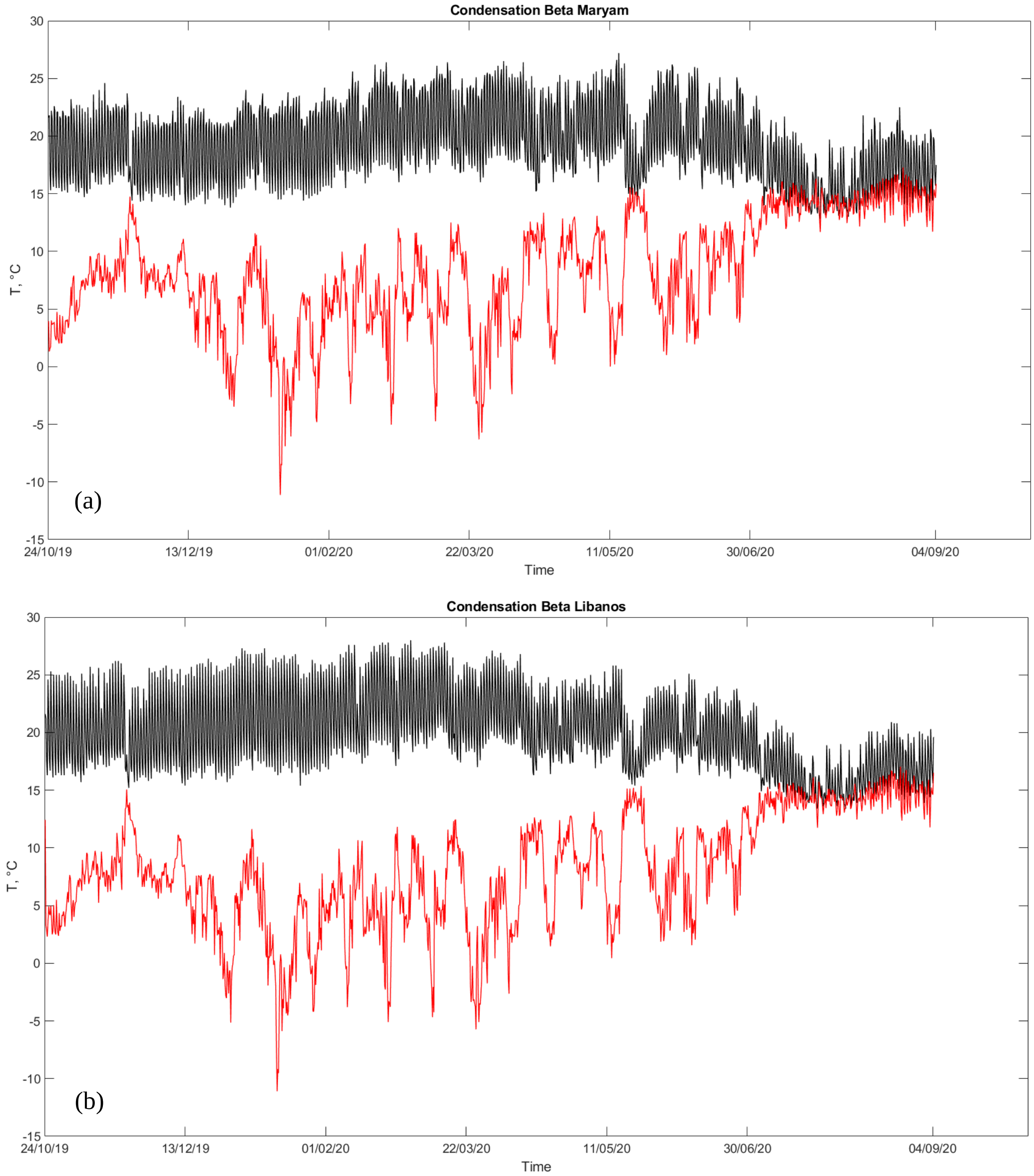

Figure 3. Variation of the temperature measured (black line) and the dew point calculated (red line); a). Beta Maryam, b). Beta Libanos

The condensation happens simultaneously in both places, with much more episodes for Beta Maryam. It appears only in July and August for Beta Libanos. The main difference is one episode in May for Beta Maryam. Such episodes of condensation could be a problem due to the dissolution of salts on the surface, their transport to another surface (with falling drops due to the gravity) and an accumulation in the lower parts of the buildings. Moreover, this liquid water could have facilitated the growth of micro-organisms [16]. With such low repetition rate, the possible dissolution of the surface by that condensing water should not seem to be an issue of conservation.

Comparison Medhane Alem and Beta Maryam, West façade

The probes S4 and S5 are located on the West facade of Beta Medhane Alem and Beta Maryam. An example of the measurements can be seen on Figure 4, at 18:00 every day. The difference between two facades with the same exposition is shifted during the day and the season:

- In the morning Beta Maryam is colder, and therefore more "humid" (2°C and about 7% as an average). This difference is probably due to the sun which hits directly Beta Medhane Alem in the morning;
- At noon, Beta Maryam is a bit warmer and a bit dryer (1°C and 2% as an average), but during the wet period this difference in RH is much more important, about 10%. This difference for T can be attributed to the sun, which hits directly the facade of Beta Maryam. For the RH, it could be attributed to the fact that Beta Maryam is less dug and is located in a more open environment. Thus, there is a possible impact of the shelter, which is less covering. The air can circulate more easily with a better air renewal and an effect of less accumulation of humidity;
- •At 18:00, the difference between the 2 churches is less accentuated; it alternates from positive to negative values from the beginning of the period to the end. But Beta Maryam is more often colder and therefore more humid than Medhane Alem. Between noon and 18:00, there is an increase of RH in Beta Maryam but not in T during the wet season. During the rainy periods that comes with an increase of air humidity, there is a systematic increase in the magnitude of RH, which is more pronounced in Beta Maryam. These greater fluctuations in Beta Maryam underline a rebalancing of the humidity within the environment (Figure 3; RH at 18:00). On the contrary, the more confined state can justify these smaller deviations in Beta Medhane Alem. Once again, for the conservation issues, the main impact could come from the difference in humidity and the possible cycle of crystallisation/dissolution of salt.

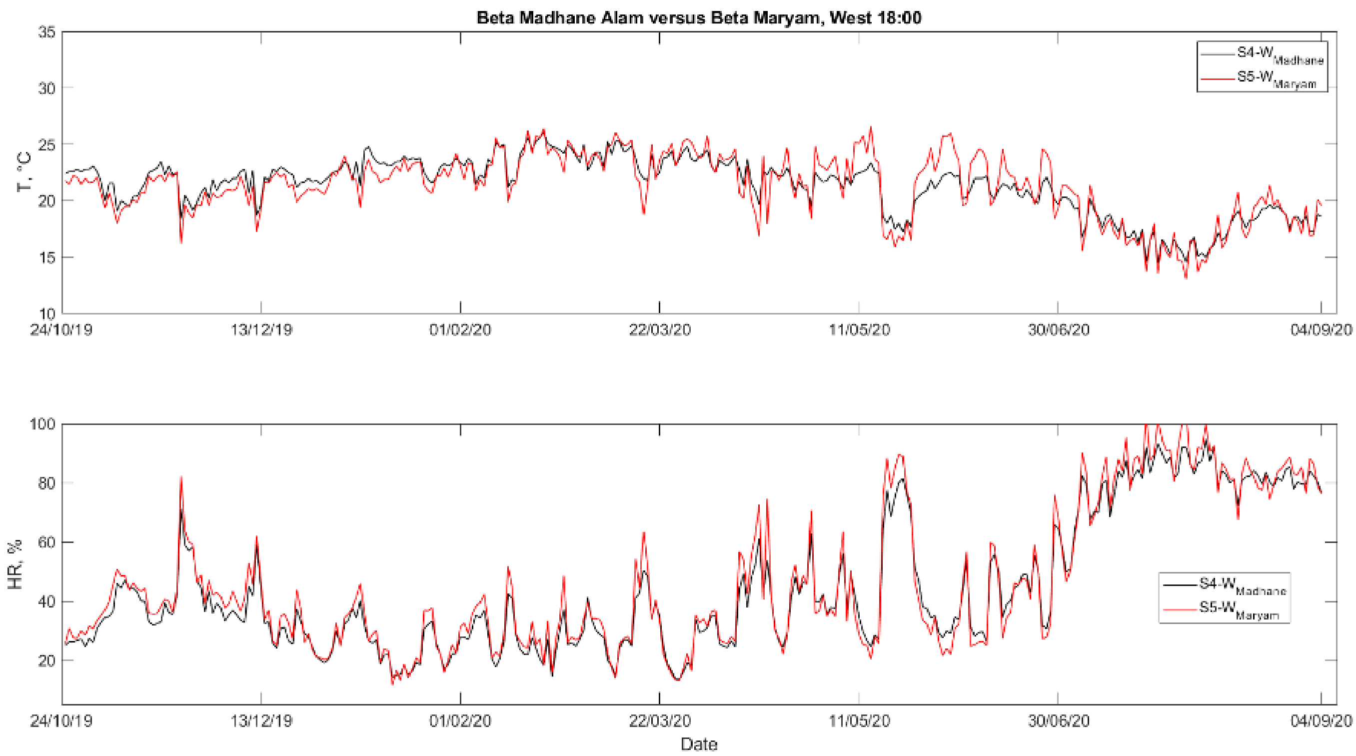

Figure 4. Variation of *T* and *RH* for Beta Medhane Alem (black line) and Beta Maryam (red line) at the same hour of the day, 18:00

Conclusive Remarks

During this climatic monitoring, two parameters were measured - the temperature and the relative humidity, with the dew point ′being calculated in different areas outside and inside the churches. It appears that the microclimate on the rock facade of the different churches (outside) is very stable around 18.7±2.4°C with an annual average temperature respectively $Tmin$=13.8±0.9°C and $Tmax = 26.5 \pm 1.0°C$, whereas the measurements for the interior climate in the churches (S3 and S6 probes) are respectively, $Tmin$= 16.7±0.1°C, and $Tmax$= 20.6±0.7°C, highlighting the thermal inertia of the rock.

Humidity variations are much greater. Although the annual average RH is between 48.3 and 53.6 %, saturation (100 %) is easily reached during rainy periods, the lowest values are respectively between 9 to 12% RH outside and 16 to 17% RH inside the churches. The difference of RH in respect to the seasons is great, so the thermo-hydric behaviour of the rocks seems therefore mainly moisture-dependant. Some particularities can be highlighted mainly depending on the orientation of the facade or the direct surrounding and especially the buffer effect related to the presence of a shelter. This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.2. Roughness Analysis

Wall 1

During the measurement of 3D surface roughness, the first data to be determined is the datum plane. Extending the one-dimensional Gaussian filter to two-dimensional, the 2D Gaussian function can be used to extract the 3D surface contour datum [17]. The height will be calculated as the difference between this datum plane and the measured points.

Before the calculation of the roughness parameters, it is essential to study the distributions of the points calculated. Indeed these distributions (Figure 5) will inform about the behaviour of the roughness, whether it is a bump or a hollow. It appears that the distribution for the wall 1 is shifted in the negative range of values. This kind of behaviour is typical for levelled surfaces in the industry or occurs naturally due to the erosion, because peaks are more easily removed than valleys [18].

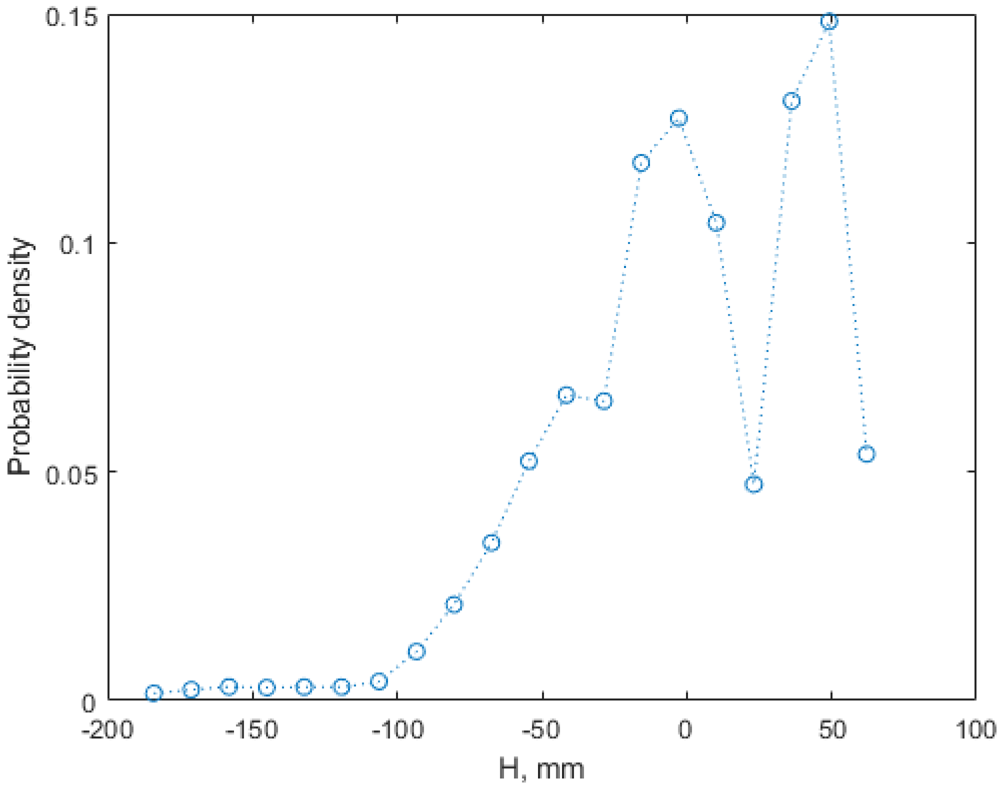

Figure 5. Density probability of the calculated height for the wall 1

Wall 2

The same procedure was applied to the wall 2. As a result, the distribution on the wall 2 is symmetrical between the negative and the positive value. It means that there are non-external phenomena to level the surface, in valley or peak, as seen on Figure 6.

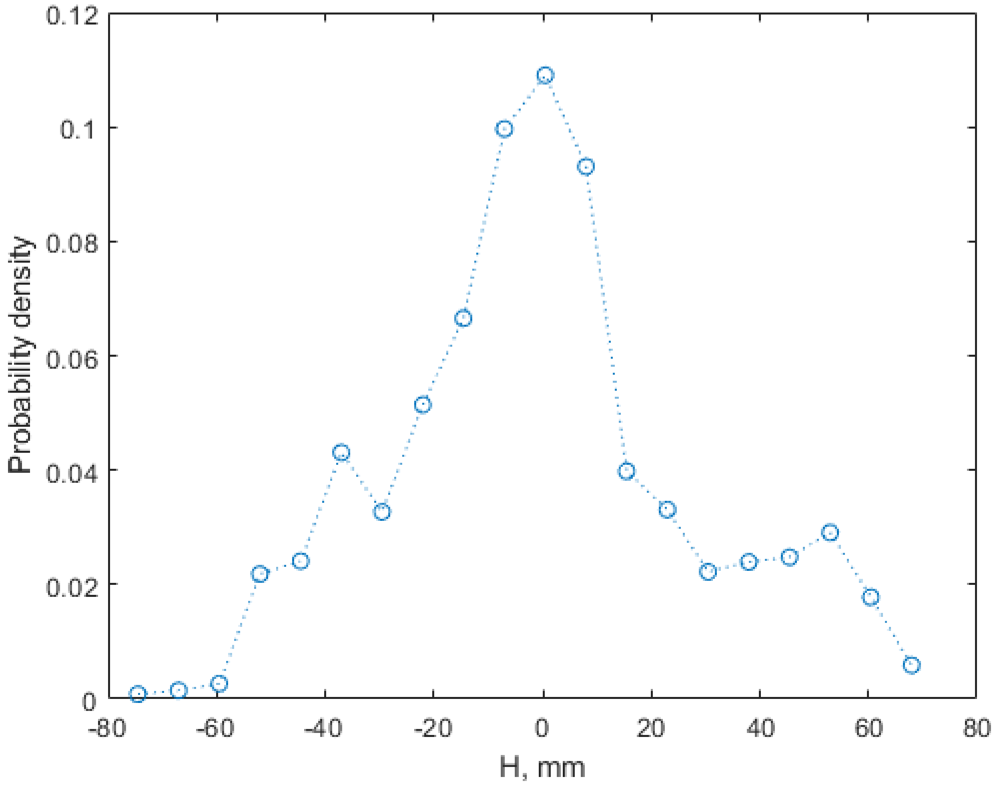

Figure 6. Density probability of the calculated height for the wall

Comparison of the 2 Wall Areas

The distributions of the heights are clearly different between the two areas. On the wall 1 the distribution is due to a levelled phenomenon on the surface, while on the wall 2 there is no preferential phenomenon responsible for a particular distribution of height. This phenomenon can be attributed to the rain and its impact on the surface, as the wall 1 is not covered by a shelter. This means that the presence of a protection can be involved in the limitation of the alteration by erosion caused by rain. In addition to that, it is well known [16] that increase of the roughness will increase the probability of colonisation of algae, and then the alterations. It is then important to reduce the mechanisms provoking those alterations. The different parameters used for roughness evaluation are then calculated with the distribution of the height in accordance with the standard ISO 2578 [13, 19].

Table 2. Calculated parameters of the studied areas

Parameters	Wall 1 (mm)	Wall 2 (mm)
S_a	34.9	21.3
S_q	26.1	17.2
S_v	-190.4	-78.2
S_p	68.5	71.7

On the one hand, the average roughness has a difference of 40% between the two areas; the wall 2 is less rough than the wall 1. This is clearly visible on the field and the 3D reconstruction. On the other hand, the main difference between the two areas is the deepest valley, with a difference close to a factor 3. As a result, the measured roughness parameters underline the positive effect of the shelter on the rock preservation, due to their positive effect on the reduction of rainfall erosion. In addition, there is also an indirect effect on the reduction of algae development due the dry surface persistence on the long-time which limits microorganism's implantation and growth.

3.3. Transient gas Permeability

Two air permeability measurements were performed by direct contact of the permeameter and the rock surface on each of the two walls (1 and 2). The measurements were carried out regularly from the lower part (h = 63 cm) to the upper level of the wall (h = 238 cm). Ten successive permeability measurements were thus determined according to those vertical profiles. The change of permeability as a function of the height of measurement is presented in Figures 7 and 8.

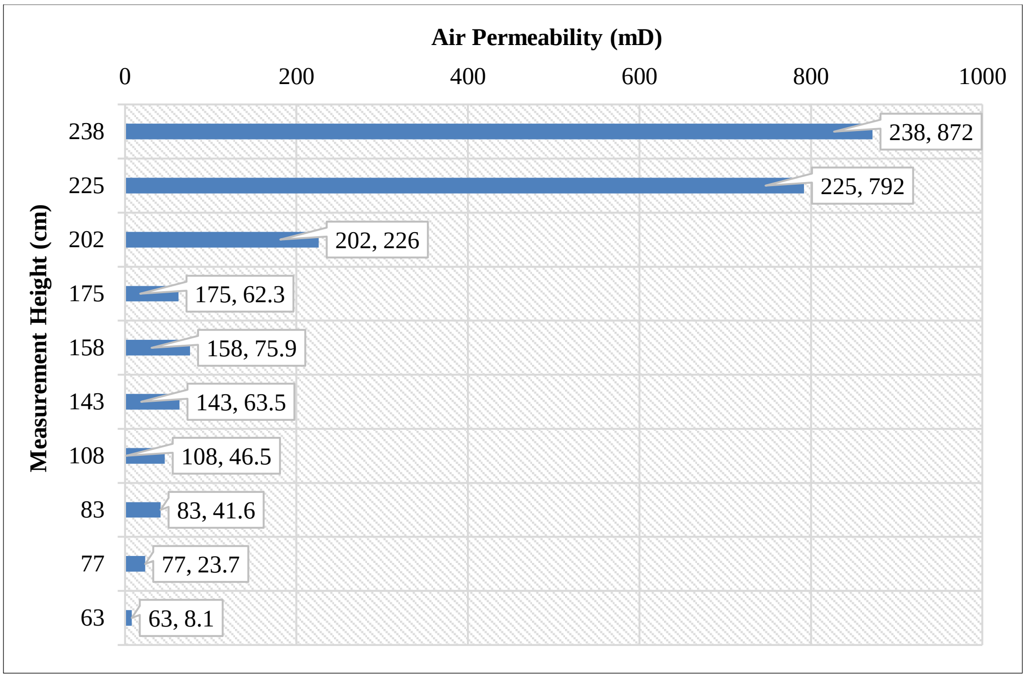

Figure 7. Air permeability profile (wall 1)

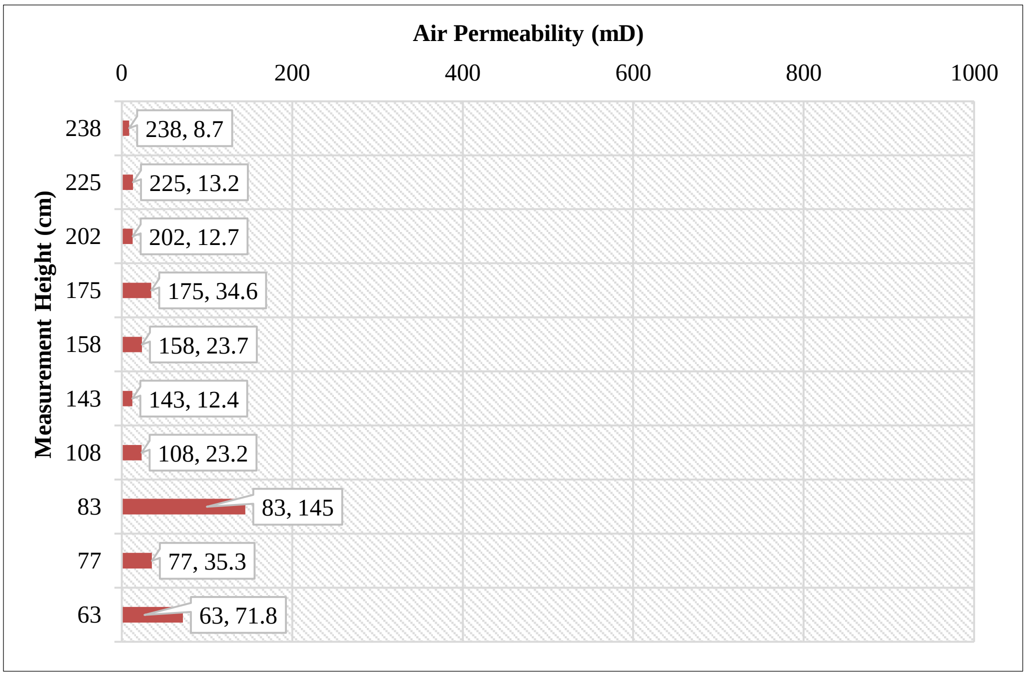

Figure 8. Air permeability profile (wall 2)

On wall 1, the permeability in the lower part is around 8 to 10 mD, which corresponds to sufficient average permeability to ensure effective transfer of aqueous solutions or water through the rock matrix and the crack on a human scale. These values are consistent with the order of magnitude of common K values measured on poorly consolidated volcanic tuffs such as scoriaceous basalts in the Lalibela site. In the highest layers of the profile, permeability gradually increases closer to the top of the wall, i.e., to the level of the rocky soil. At a height of 238 cm from the wall (Figure 8), the permeability reaches excessive values of up to 800 mD. These very high values underline the high permeability of the rock, linked to an increase in its porosity due to a dissolution mechanism which affects some mineral phases or interfaces. Such evolution contributes to the surface rock disintegration of its surface.

On wall 2, not affected by rainwater infiltration, the permeability values are between 9 and 145 mD. Unlike the evolution on wall 1, no increase in permeability is noted with the height of the measurement. On the contrary, permeability values seem to reach an average and relatively constant value of around 20 ± 10 mD. This reflects the homogeneous microstructure and a cohesive matrix of the scoriaceous basalt in this wall area over a certain thickness of rock, which is favourable to its conservation. Guaranteeing homogeneity of basalt surface properties in a correct conservation state is only possible by limiting the interactions of water flow within the porous network.

4. Discussion

The microclimatic monitoring carried out brings additional elements. On the one hand, the temperature parameter appears to have a low impact on the conservation issues, by possible thermal dilation, for example. On the other hand, the relative humidity and, more generally, the presence of water, i.e., the condensation phase, can have a direct effect on the conservation issues. Water is undeniably the key factor in the rocks' decay. As a result, it appears useful to fully cover the churches to avoid the negative impact of the rain or sunlight.

Investigations carried out in the field with complementary analytical techniques allowed us to characterize the impact of the shelter on the scoriaceous basalt from macro to the microscale. These methods deal with the physical and structural properties of rocks (roughness, permeability). Analysis of two sections of the wall, one protected from direct rain for 12 years and the other periodically exposed to runoff, shows various states due to liquid water, identified as a major factor in the basalt degradation. Exposure to water leads to irreversible damage, as:

- An increase of macro-roughness following the differential leaching of minerals from the rock;
- An increase of surface permeability linked to cracks formation and the opening of grain boundaries [20] induced by dissolution.

In the field of stone/rock conservation, the main risk of deterioration lies within salt crystallization, which results from a supersaturation state and occurs in the preferential evaporation zones of the solutions. Therefore, the development of salt damage requires two preconditions:

- A transit phase to concentrate the salts: water;
- Chemical compounds in sufficient quantity to form soluble salts: ions.

At Lalibela, an outdoor cultural heritage site subjected to periods of monsoon, the context is different from a monument built with matched materials because the rock in place can release ions present in its minerals (smectites, zeolites). These two families of minerals already studied have a strong affinity and sensitivity to water (in liquid and vapor form). Release of great amounts of Ca and Na ions in solution is thus possible. These cations can be involved in the formation of destructive salts after association with the anions present in solution (nitrates from decomposing organic matter).

5. Conclusion

On the site, damages linked to the salt crystallization (mainly alveolization) occur in regularly wet zones such as the walls of the counter-scarps transporting ions process in solution is decisive in the initiation and the alteration kinetics of the rock. Analysis coupled with on-site observations suggests that deterioration linked to liquid water and the persistence of a state of high water content is more damaging than the deterioration risk linked to the salt crystallization process, which occurs in priority areas in dry areas. This risk cannot be totally ruled out, but it can be reduced by the integration of current practices of stone conservation, such as desalination. As water is the key factor in the very harmful alteration concerning the conservation of scoriaceous basalt as a heritage material in humid natural environments, it appears useful to fully cover the churches.

6. Declarations

6.1. Author Contributions

Conceptualization, R.M. and A.G.; methodology, J.D.M.; software, D.G.; validation, J.D.M., R.M. and A.G.; formal analysis, J.D.M., A.G., R.M., and D.G.; investigation, B.T.G.; resources, R.M., and A.G.; data curation, D.G.; writing—original draft preparation, J.D.M., B.T.G., and D.G.; writing—review and editing, D.G.; visualization, A.G.; supervision, R.M.; project administration, R.M.; funding acquisition, R.M. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in article.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Acknowledgements

French ministry of Europe and foreign affairs, all the religious community of Lalibela, Ethiopian ministry of Culture.

6.5. Institutional Review Board Statement

Not applicable.

6.6. Informed Consent Statement

Not applicable.

6.7. Declaration of Competing Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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