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EVALUATION OF WEATHERING EFFECTS DUE TO SURFACE AND DEEP MOISTURE IN A ROMAN ROCK TOMB: LUKIANOS MONUMENT KONYA (TURKEY)

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ABSTRACT

Water is an integral component of direct and indirect decomposition processes that may lead to the deterioration of stone building materials in cultural heritage. Since the deterioration effects caused by water may cause irreversible problems in the whole monument, the detection of water is extremely important. Although there are many methods of moisture measurement (nuclear magnetic resonance, electrical resistance measuring, infrared thermography, radar, moisture meter) in the literature, there is no study in which deep and surface moisture values are evaluated together in monuments. For this purpose, the Lukianos Monument (Beyşehir, Konya-Turkey), which was created by carving on the rock surface, was investigated for a better understanding of the causes and development of the deterioration mechanisms of cultural stone heritage using surface moisture (SM) and deep moisture (DM) meters. It was aimed to determine the behavior of surface and subsurface water in the stone material by applying both methods. For this, firstly, deep and surface moisture data were processed on orthophoto obtained from the photographs of the monument. The P-wave velocity (Vp) test was also performed to determine the deterioration effects caused by water, which is mostly present in the form of moisture in structures on the rock. According to the results obtained from the study, contour scaling type deterioration and lower P-wave velocity values were obtained in parts where low DM values were determined in response to high SM values. The development of biological colonizationwas commonly observed in the regions with high moisture (surface and deep) values.

KEYWORDS: Lukianos monument, surface moisture, deep moisture, deterioration

1. INTRODUCTION

Cultural heritage, including temples, theatres, castles, and tombs, created by ancient civilizations are important cultural properties that bear the traces of ancient cultures to the present. Among these constructions, rock tombs are structures built by carving on the parent rock in high, sheltered places dominating the region. This kind of monuments, which generally built for the leading persons of the community, with different plan types and decoration features, are important cultural heritages that should be preserved with their historical and artistic values (Fig. 1).

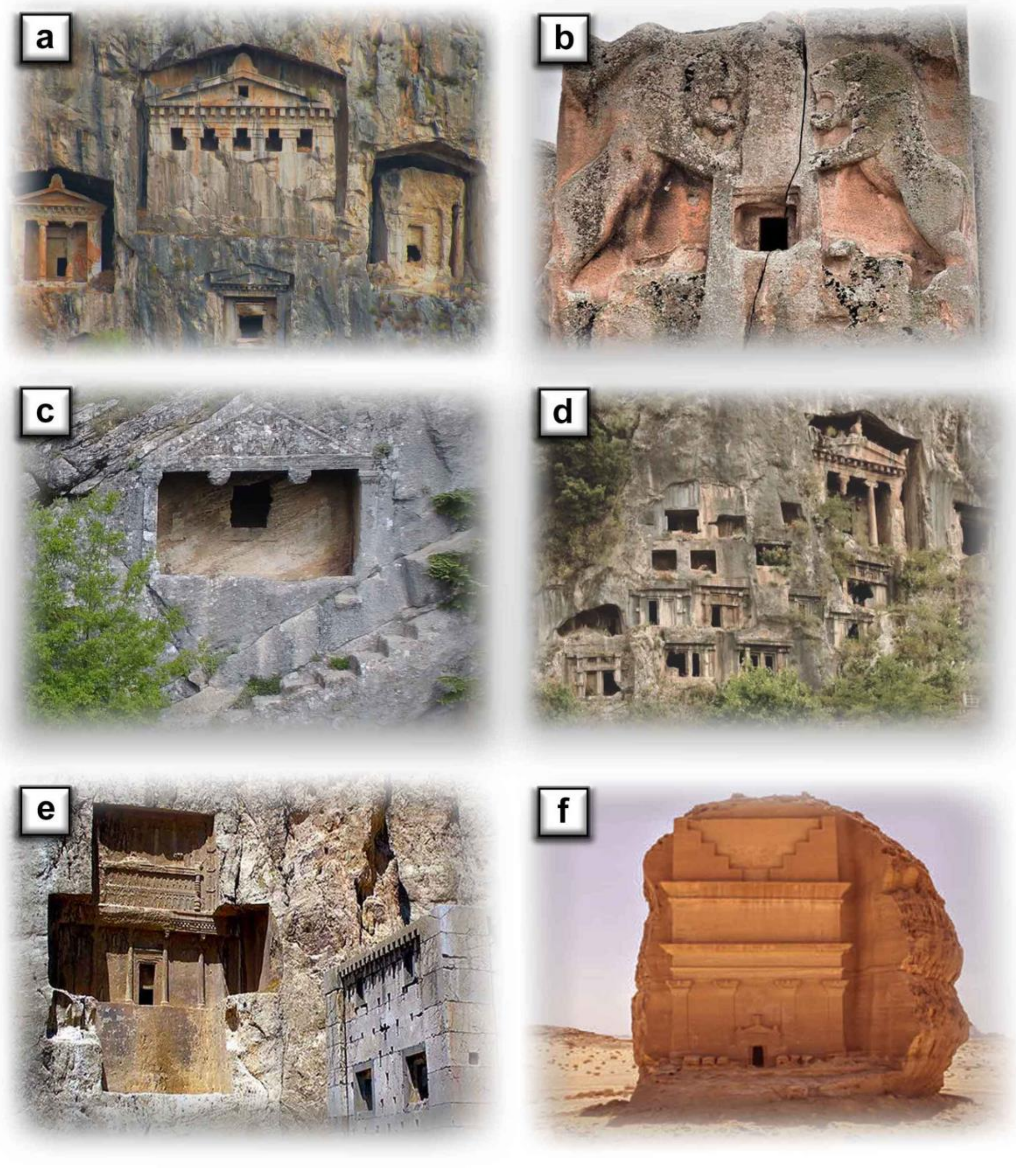

Figure 1. Some examples of rock tombs; a) Kaunos (Muğla, Turkey), b) Lion (Afyonkarahisar, Turkey), c) Isauria (Karaman, Turkey), d) Amyntas (Muğla, Turkey), e) Naqsh-e rustam (Fars, Iran), f) Qasr al-Farid (Al Madinah, Saudi Arabia)

However, in these monuments that reliefs are directly open to atmospheric agents, deteriorations may occur in time, and irreversible problems may be encountered within time (El-Gohary and Al-Shorman, 2010; Elhagrassy and Hakeem, 2018). The most effective direct and indirect factors in the deterioration process in these structures is water (Çelik and Kaçmaz, 2016; Al-Naddaf, 2018; Korkanç, 2013). The amount and movement of water that can reach rock pores play significant roles in the acceleration of the deterioration process (Tomašić et al., 2011). Therefore, moisture control plays a significant role in transferring cultural heritages to future generations by preserving it. For this purpose, many researchers have recently used non-destructive testing techniques (NDT), such as nuclear magnetic resonance (NMR), electrical resistance measuring (ERM), infrared thermography (IRT), radar and moisture meter (microwave and dielectric), either alone or in combination, in order to determine the origin and movement of water in cultural monuments (Capitani et al., 2009; Di Tullio et al., 2010; Rehorn and Blümich, 2018; İnce et al., 2018; Korkanç et al., 2018, 2019; Tosunlar et al., 2018, 2019; Bozdağ et al., 2020; Hatir et al., 2019; Ruiz Valero et al., 2019, Orr et al., 2020). NMR is non-destructive technique which measures the hydrogen signal of the moisture and that was applied directly to the monument. ERM is another NDT that measure moisture indirectly by measuring the electrical resistance of the building stone which makes measured resistance dependent on the dielectric property of the building stone. The wave applied in the high-resolution radar method greatly affects the amplitude of the wave depending on the water content in the building block, thus making it possible to determine the water content close to the surface with this method. Among these methods, the IRT method allows for a rapid determination of water behaviour on the material or wall surface. However, the IRT cannot evaluate the moisture content quantitatively apart from causing errors under environmental and microclimatic conditions (Rosina and Ludwig, 1999; Capitani et al., 2009). Electrical resistance measuring can be affected by factors such as the density of the material, sunlight, and shadow (Ruiz Valero et al., 2019). While microwave sensors provide useful information about the general distribution of water in homogeneous structures, radar measurements are more useful in determining the local distributions of water in masonry structures (Orr et al., 2020). Surface moisture meters provide important information for determining the presence of moisture on the surfaces (approximately 4 cm) where rocks are in direct contact with atmospheric effects (precipitation, temperature, etc.). Although this non-destructive testing method (NDT) provides significant contributions to the investigation of deterioration processes caused by water, it cannot provide information about moisture penetrated into the rock. Therefore, only the surface moisture meter leads to inadequacies in understanding the deterioration behaviours and processes of rocks caused by water. Determining the moisture content in the monuments using the multi-technical approach can help achieve better results in clarifying the deterioration process in these structures. Many researchers, who took this situation into account, use surface moisture meters together with other NDT methods (Schmidt hammer rebound, P-wave velocity, IRT) to investigate deterioration in cultural heritage elements (İnce et al., 2018; Tosunlar et al., 2018; Bozdağ et al., 2020; Hatir et al., 2019).

In this study, the visualization of the variation of moisture in the Lukianos Monument (Beyşehir, Konya-Turkey) was prepared using surface (SM) and deep moisture meters (DM) in combination to determine the origins and progress processes of the deterioration mechanisms observed in the monument. Thus, the movement of water penetrated on and into the rock surface was evaluated as a whole. Furthermore, the P-wave velocity (Vp) surface map was created to investigate the change in rock properties caused by deterioration effects in the rock. The relationship between the types of deterioration observed in the monument and moisture change (surface and subsurface) was determined by NDT methods.

2. MATERIAL AND METHODS

2.1. *Description of the Lukianos monument*

The Fasıllar region, which is located approximately 70 km south-west of Konya city, was home to the Hittite, Roman, and Byzantine civilizations as a result of its important location. While this region stands out with the quarry, where rock monuments were built during the Hittite period (Bozdağ et al., 2020), it attracts attention with its hippodrome where horse races were held during the Roman period (Baldıran et al., 2008; Rojas and Sergueenkova, 2014). The most remarkable work of the Roman period in Fasıllar is the Lukianos Monument (Fig. 2a, b). This monument was built approximately 10 meters above the ground. It consists of a vaulted niche and a horse figure next to this niche. In the Greek inscription just below the monument (Sterrett, 1888), there is information that Lukianos died at a young age (Baldıran et al., 2008) (Fig. 2c). As understood from this inscription, the monument is a rock tomb built in the memory of Lukianos, who was a young Roman rider. This monument consists of a horse relief 1.84 m in height and a tomb chamber with dimensions of 139 cm x 116 cm that was built with a concave plan within the discontinuities surrounding the monument (Fig. 3). Furthermore, in the lower part of the rock tomb, there is one of the oldest inscriptions describing the rules of horse racing in history (Baldıran et al., 2008) (Fig. 2d).

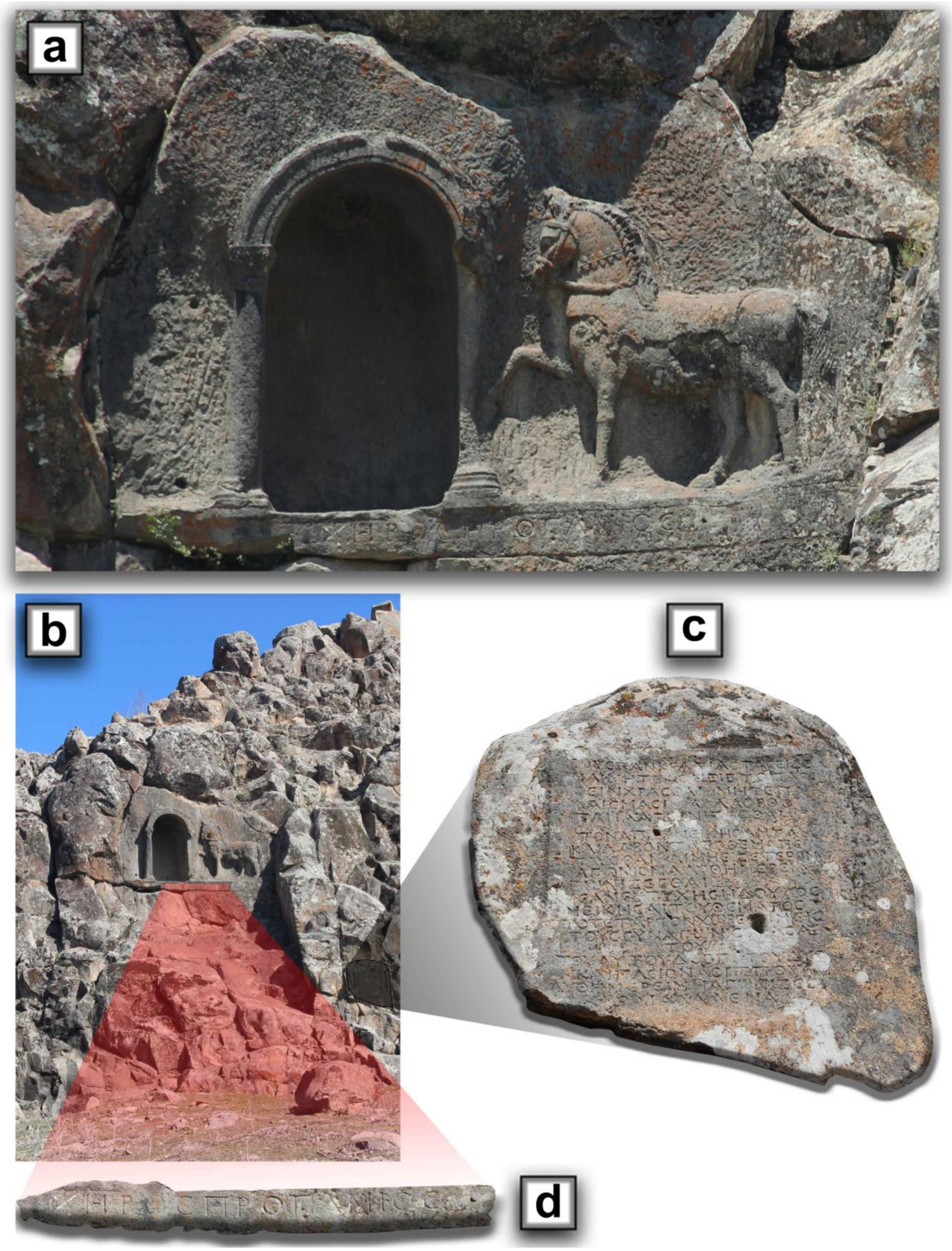

Figure 2. Lukianos Monument a) ortho-photograph b) general view, c) view of the inscription describing the rules of horse racing, d) inscription.

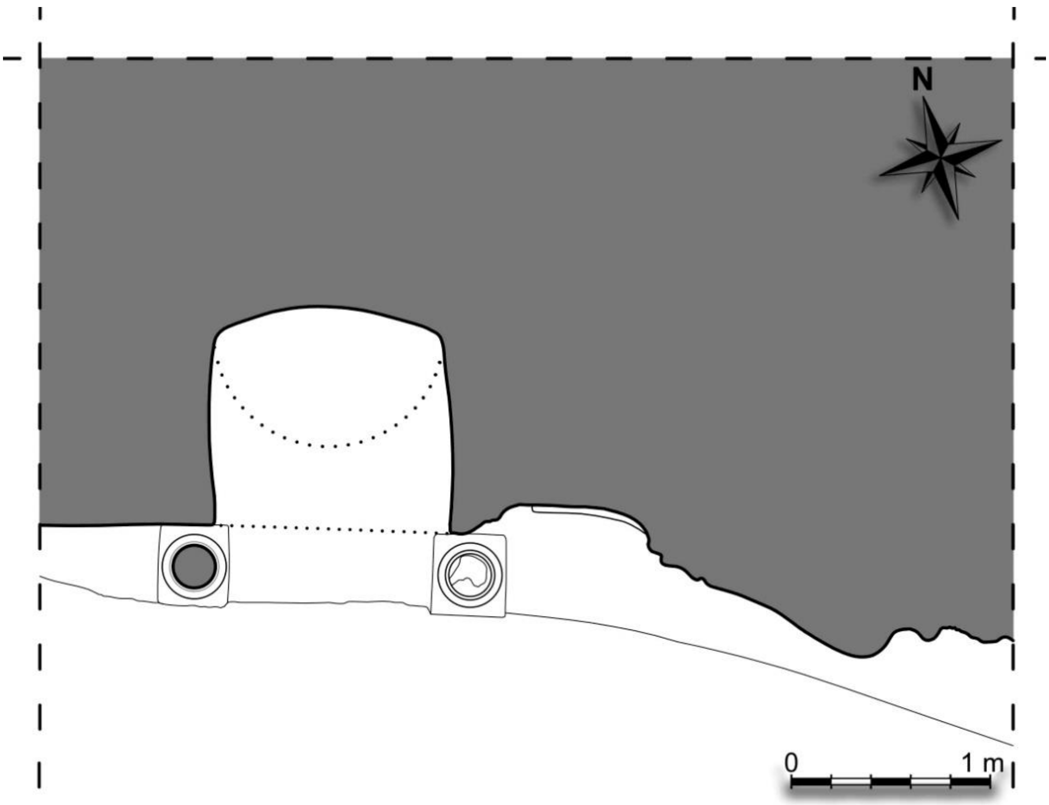

Figure 3. Plan of the Lukianos Monument.

2.2. Climatic setting

In the Beyşehir province, which has a continental climate, while the winters are snowy and cold, summers are dry and hot. The data recorded by the Beyşehir meteorology station between 1990-2019 are shown in Table 1. According to the data, the average annual rainfall in the region is 536 mm and the minimum and maximum rainfalls were recorded in June and December, respectively (Table 1). Average monthly precipitation in the region is 45 mm. The season with precipitation below this value is defined as the dry period (June-September) and the season with precipitation above it is defined as the wet period (October-May). When the temperature data in the region are examined, the lowest and highest temperatures are in January and July, respectively, and the annual temperature average is 10.99 °C. The dominant wind direction in the region is north-south direction (Fig. 4).

Table 1. Meteorological data for the Beyşehir (Konya, Central Anatolia) province in the period 1990–2019 (MGM - General Directorate of Meteorology, 2020).

Month	Temperature (°C)			Monthly total precipitation (mm)
	Average	Minimum	Maximum	
January	0.0	-4.1	4.2	84
February	1.4	-3.1	6.0	64
March	5.0	-0.3	10.3	49
April	10.2	4.6	15.9	49
May	14.6	8.5	20.7	44
June	18.5	11.9	25.1	25
July	21.8	14.9	28.8	7
August	22.0	14.7	29.3	10
September	17.3	10.0	24.7	16
October	12.4	5.9	18.9	46
November	6.9	1.6	12.2	57
December	2.8	-1.1	6.7	85

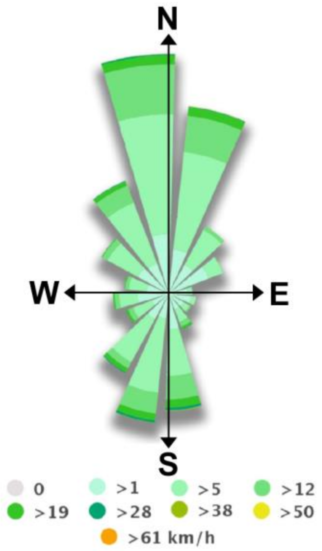

Figure 4. Wind map of the region.

2.3. Sampling Area and Geology

Upper Miocene-Pliocene volcanic rocks with dacite, andesite, rhyodacite, and rhyolite composition widely distributed in and around the Fasıllar region were defined as the Erenkilit Dağı Lava member (MTA, 2016). The units in the region, where the studied Lukianos Monument is located, are macro-light-dark gray colored and have an aphanitic-porphyritic texture. Bozdağ et al. (2020), defined the type of volcanic rocks in the region as dacite.

2.4. Experimental Procedures

The experimental procedure of this study was performed in two stages: in-situ and laboratory studies. In the first stage, homogeneous block samples with textural features representing the rock unit hosting the monument were collected for experimental studies from ancient quarries in the region. Then, photogrammetry studies were first performed to create the ortho-photography of the monument. For this purpose, sequential photographs of the relief were taken by a Canon EOS 600D camera. Afterward, the ortho-photograph of the monument was obtained with aReCap program (Fig. 2a). Last in the in-situ stage, a CAD drawing of the monument was made on the ortho-photographs using the Autocad software.

The contours of the SM, DM, and Vp values measured in the Lukianos Monument were obtained using the Surfer 13 program, and the NDT surface maps of the monument were created by transferring these contours on the CAD drawing.

The SM and DM distribution maps of the monument were prepared to determine the change of water on the rock surface and deep (subsurface), and to investigate the effect of this change on the deterioration process. A Trotec T660 test device was used for the measurements of surface moisture. This device operating at a precision of ±0.1%, according to the dielectric measurement principle can perform measurements at a maximum penetration depth of 40 mm. The Trotec T610 device was used in the measurements of subsurface deep moisture. This device with a maximum penetration depth of 300 mm operates according to the microwave measurement principle. The surface and deep moisture measurements applied to the determined measurement points were repeated three times in each point, and the mean values were recorded.

The P-wave velocity distribution map was prepared to determine the effect of the atmospheric deterioration in the monument. The Vp values were determined indirectly both in situ and in the laboratory by the UK 1401 device according to the method proposed by ISRM (2007). The UK 1401 device consists of two integrated probes, one receiver and one transmitter with a 20 cm distance between them, with a measuring capacity of 1500-9990 µs. All performed measurements were repeated at least three times according to the relevant experimental methods, and their mean values were recorded. These measurements were performed under the weather conditions of dry season.

In the laboratory stage, NX diameter core samples were prepared from the blocks collected from the ancient quarry in the region where the monument is located in order to determine the index-strength properties. The index (porosity, dry density, P-wave velocity), mechanical (uniaxial compressive strength), and capillary water absorption values of the rock were determined in accordance with the relevant test methods and standards on these core samples (ISRM, 2007; ASTM D7012, 2014; TS EN 1925, 2000). Porosity and water absorption values by weight were determined using saturation, length, and diameter data. Dry density was determined according to the test methods proposed by ISRM 2007. While the volume of the samples was determined by the average of several caliper readings, their dry mass was measured by a scale with an accuracy of 0.01 g. Dry density values (ρd) were obtained from the ratio of sample weight to sample volume. The capillary water absorption test was performed to determine the movement of water in the rock, in accordance with the methods recommended in TS EN 1925 (2000) standard. Uniaxial compressive strength (UCS) tests were performed on the core samples with a diameter of 54 mm and a length/diameter ratio of 2.0-2.5 at a loading rate of 0.5-1.0 MPa/s (ASTM D7012, 2014). The tests were repeated at least five times, and the mean value was determined as the UCS value of the rock.

3. RESULTS AND DISCUSSION

3.1. Geomechanical properties of the Lukianos monument stone samples

Dry density (ρd), porosity (n), P-wave velocity (Vp), and capillary water absorption coefficient (C) values of the rock unit, where the monument was carved, were measured as 2.20 g/cm^3, 7.28%, 4.33 km/s, and 7.12 g/m^2/s$^{0.5}$, respectively. The UCS value of the hosting rock was 69.60 MPa, and it was included in the category of "medium resistance" according to the UCS classification proposed by Deere and Miller (1966). According to C classification of the Snethlage (2005), the C values of the all samples classified as "slightly absorbing rock".

3.2. Deterioration observed in the Lukianos monument

Rock surfaces are modified in natural outcrops depending on the interaction between the atmosphere and the rock. Biological factors are natural conditions that have persistent adverse effects on historical buildings. Because the effects of these factors are continuous and slow, the measures taken are mostly neglected. Primary biological effects come from plants that grow on buildings, which can cause them harm (Korkanç and Savran, 2015). The definition of biodeterioration includes the changes in a material's properties experienced by living organisms as a result of their activities for survival in a way that is not quite preferred. These undesired changes are the results of chemical, mechanical and physical impacts (Guillitte, 1995; Garcia-Valles et al., 2000; Garcia-Valles et al., 2002; El-Gohary and Al-Shorman, 2010; Miller et al., 2012; Elhagrassy and Hakeem, 2018). In this study, the types of deterioration observed in the Lukianos Monument were determined according to the definitions in the ICOMOS-ISCS (2008) dictionary. According to ICOMOS-ISCS (2008), contour scaling (Fig. 5a), discoloration and deposit (Fig. 5b), rounding (Fig. 5c), crack (Fig. 5d), biological colonization (Fig. 5e and f), and human damage (Fig. 5g and h) types of deterioration were observed in the Lukianos monument. Among the deterioration anomalies of atmospheric origin, the section with the highest level of damage was observed in the abdominal region of the horse relief. High SM (84%) and low DM (46%) were found in this region. High moisture content on this surface accelerated atmospheric effects and led to the development of contour scaling, which is the advanced stage of the deterioration process (Fig. 5a). In the mentioned part of the relief, the particles disintegrated as a result of contour scaling formed discoloration and deposit under the abdominal region by combining with infiltration water (Fig. 5b). Furthermore, the effects of infiltration water and wind led to the rounding anomaly in the foot and tail parts of the horse relief over time, which have sharp lines (Fig. 5c).

While the discontinuities limiting the monument are of geological origin, the absence of the continuity of the joint, which was observed in the lower part of the tomb chamber of the monument, in the rock mass indicated that the monument was developed anthropogenically during the construction phase or later on (Fig. 5d). Another problem caused by moisture in the monument was the formation of biological colonization. The development of lichen was commonly observed in the regions with high moisture and rough rock surface (Fig. 5e). Furthermore, the development of higher plants was also found among the joint in the monument (Fig. 5f). Regular maintenance of the place to get away from the negative effects of biological activity in stone surfaces should be done (manual cleaning, laser cleaning, herbicides, etc.).

The biggest problem in the tomb monument other than the effects of deterioration caused by water was vandalism. While hammer blows (Fig. 5g) were found in one of the columns in the tomb due to insensitivity to cultural heritage and treasure hunting, the other column carved into the bedrock, the composition of which was dacite, completely disappeared (Fig. 5h).

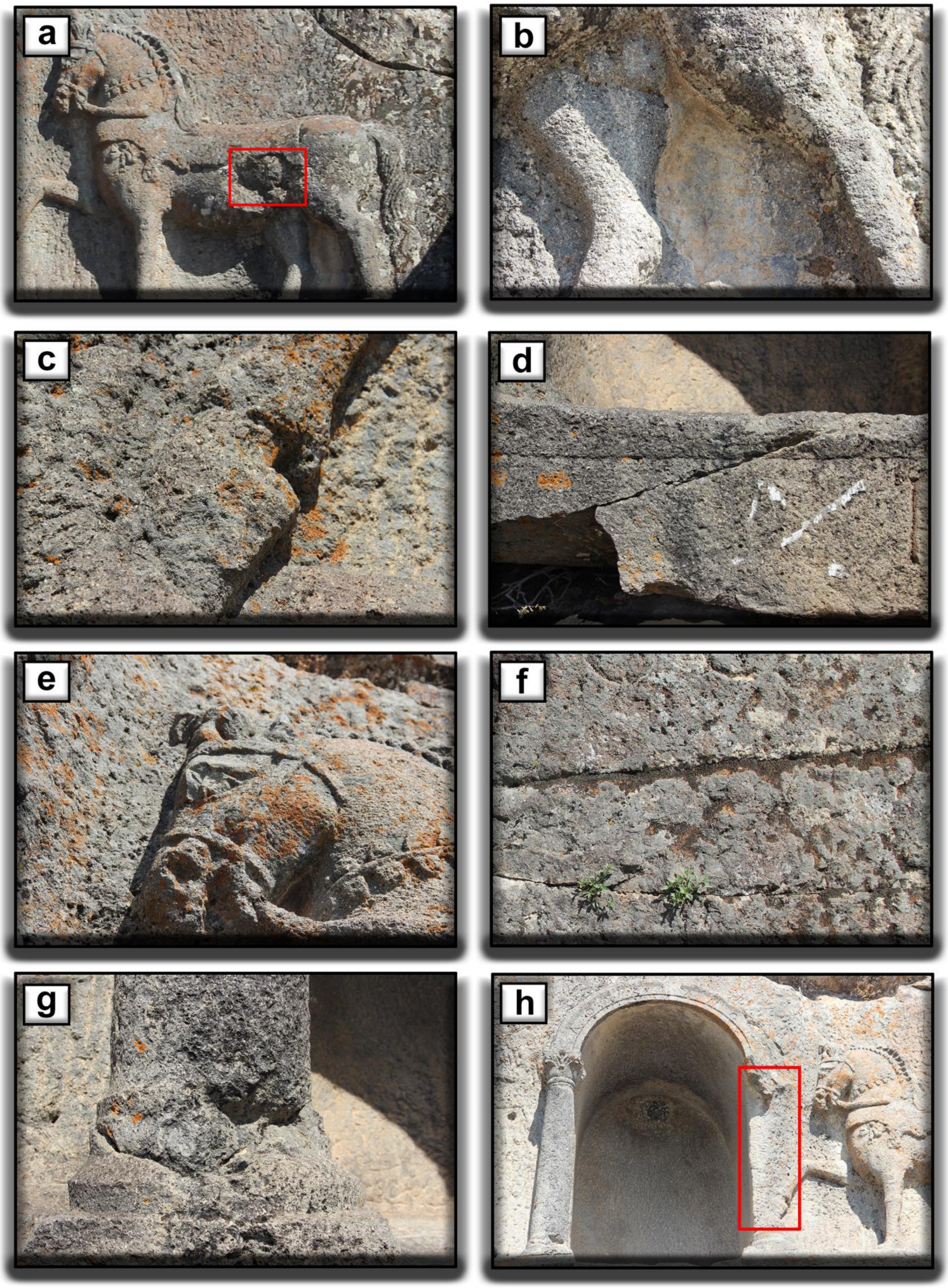

Figure 5. Views of deterioration in the Lukianos Monument; a) contour scaling, b) deposit and discoloration, c) rounding, d) crack, e) lichen, f) higher plant, g) human effect, h) missing part.

3.3. Evaluation of NDT results

The most effective factor for understanding the deterioration processes in stone-built cultural heritages is the determination of the presence and movement mechanism of water penetration into the rock body (e.g., İnce et al. 2018). Water with an active role in deterioration processes penetrates into buildings through two different ways: capillary and/or infiltration (Sanjurjo-Sanchez and Alves, 2012; Daoudi et al., 2017). Because of the location of Lukianos Monument that positioned above the groundwater table on a steep scarp approximately 10 meters higher than the mountain front floor, there is no capillary water effect in the monument. The presence of water that led to the deterioration of the monument is associated with precipitation and infiltration effects. When the prepared SM map was examined, the moisture was particularly effective on the discontinuities surrounding the monument, the inner part of the tomb chamber, and the convex abdominal part of the horse relief (Fig. 6). While the SM ratios around the discontinuities surrounding the monument varied between 58-68%, they reached up to 84% in the abdominal part of the relief. While the values on the walls of the tomb chamber were 60%, the values in other sections were below 54%. High SM values in the tomb chamber were due to shadow effect.

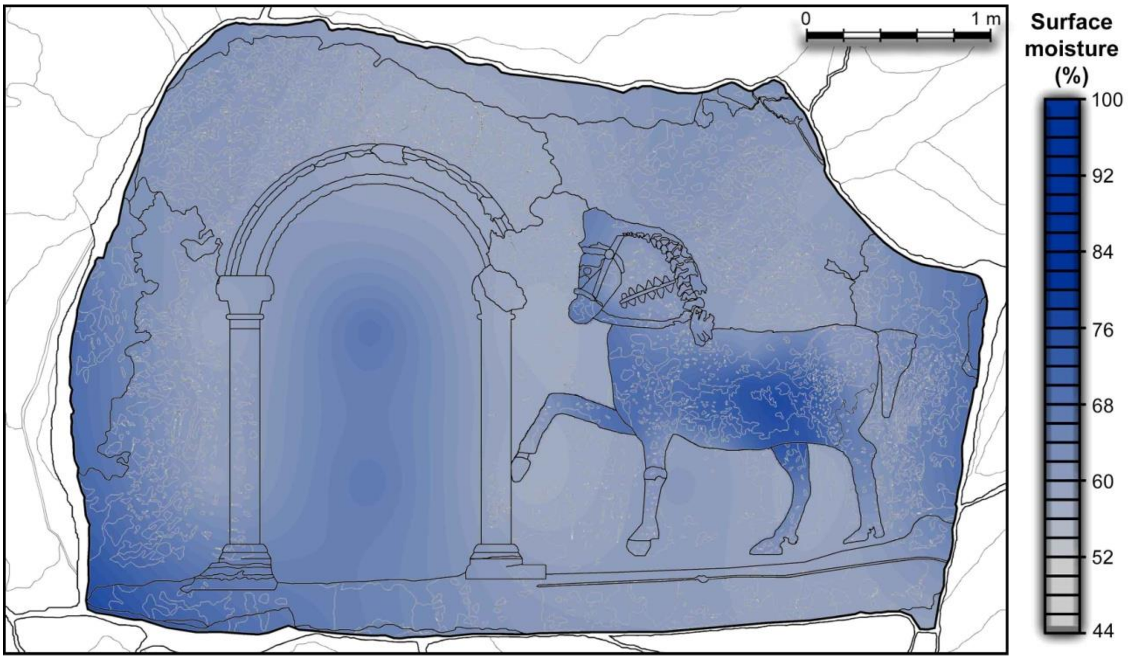

Figure 6. Maps of the distribution of surface moisture (SM) test values of the Lukianos Monument.

When the DM surface map of the monument was examined, it was observed that the moisture values varied between 44-66% (Fig. 7). While the highest values in the DM map were concentrated in the tomb chamber with the continuities surrounding the monument, the lowest values were observed in the abdominal part of the horse relief. When the two surface maps prepared were evaluated together, although there was an average of a 20% moisture difference between DM and SM, these values reached up to 40% in the abdominal part of the relief.

The P-wave velocity test provides fast and practical detection of defects such as gaps, discontinuities, and cracks occurring due to the deterioration processes in rocks. In the study, according to the surface map of P-wave velocity, values in the monument were between 1.2 and 4.2 km/s, and the lowest value was in the abdominal part of the horse relief (Fig. 8). P-wave velocity values between 1.8-2.4 km/s were obtained around the discontinuities, where deterioration was common, and the Vp values in other regions were quite close to ultra-sonic velocity values in the fresh surface of the hosting rock (4.2 km/s).When the abdominal part of the horse relief, was examined, low P-wave velocity values indicate that this region had a more porous structure.

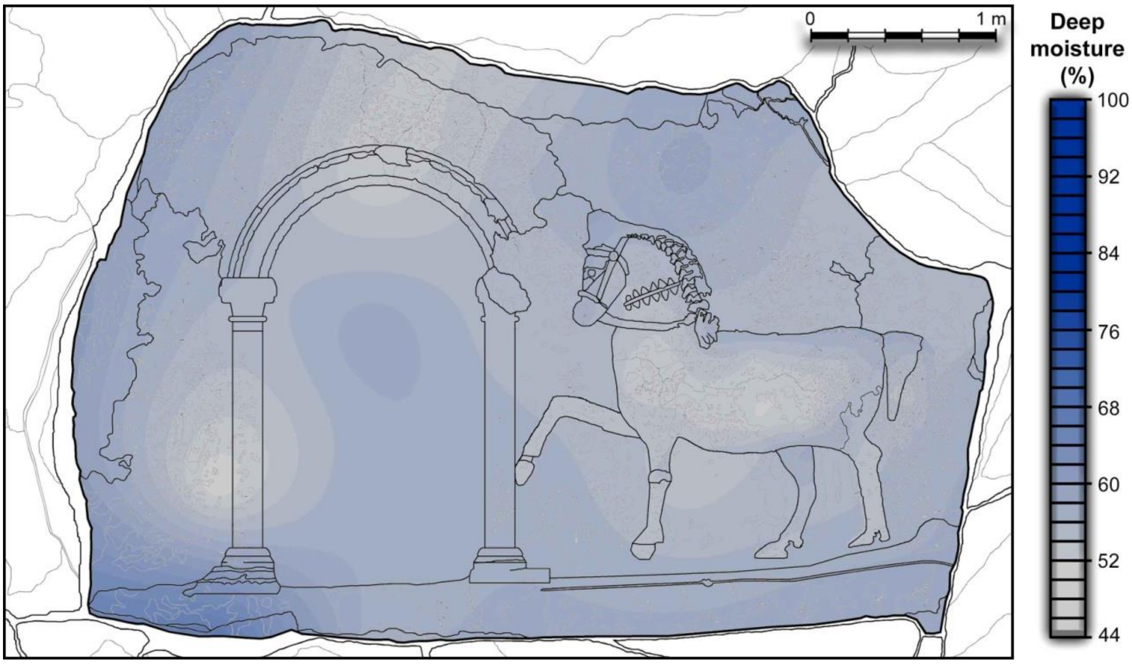

Figure 7. Maps of the distribution of deep moisture (DM) test values of the Lukianos Monument.

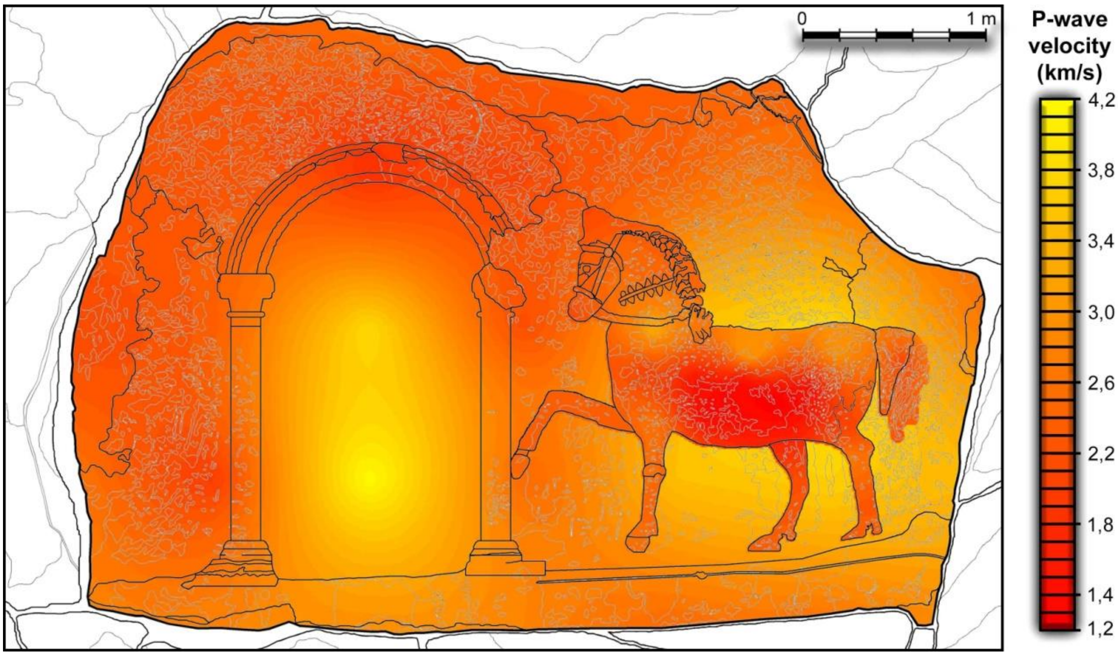

Figure 8. Maps of the distribution of P-wave velocity (Vp) test values of the Lukianos Monument.

As a result of the evaluation of the SM, DM and Vp values obtained from the monument, the difference in DM and SM values of the horse's abdomen can be explained by the variation of moisture in the rock in rainy and dry periods. In wet periods, more moisture is retained in the more porous abdominal part of the relief. The moisture moves towards the drier inner parts of the rock. This situation continues until the humidity inside the monument is balanced with the humidity in the atmosphere. In dry periods, due to the rapid decrease of relative humidity in the atmosphere, the outer surface of the horse relief's abdomen loses moisture quickly and dries out. In this case, the movement of moisture occurs from the inner parts containing higher humidity towards the drier outer surface of the rock. In the abdominal part, where water moves faster than other parts of the monument, the effect of the freezing-thawing and wetting-drying processes becomes more evident.

Many NDT methods have been used alone or together in determining the effects of water, which is one of the most important causes of degradation in cultural heritages. However, these approaches are not as satisfactory as the holistic results obtained by using SM and DM meters together in determining the presence of water in cultural heritages. It is thought that using the data obtained from SM and DM measurements together will be helpful in transferring cultural monuments to future generations.

4. CONCLUSIONS

The determination of the presence of water and its movement mechanisms in stone monuments is extremely important for the preservation of this kind of cultural heritages. In this study, the change of moisture on the surface and deep (subsurface) in the case of Lukianos Monument, a Roman rock tomb in Central Anatolia region, was investigated. It was attempted to quantify deteriorations caused by moisture change in the monument using P-wave velocity data, and the results obtained are listed below:

• Except for the tomb chamber, the regions with low P-wave velocity overlapped with the sections with high surface moisture.

• The discontinuities surrounding the monument helped the transport of infiltration water to deeper levels and increased deep moisture values in and around these regions.

• When the DM and SM surface maps of the monument were examined, it was observed that the development of biological colonization (lichen) was more common in the regions, where the moisture content increased.

• The regions, where moisture percentage values of the DM and SM maps increased, were determined as the parts where the surface deteriorations (contour scaling) also increased.

• With this study, it was attempted to reveal that the evaluation of surface and subsurface deep moisture data together would make significant contributions to the measures for a better understanding of deterioration in stone-built cultural heritages and use for their protections.

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