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Physical Characterization, Microstructural Evaluation, and Condition Assessment of Ancient Ahlat Tombstones in the Seljukian Cemetery of Ahlat (Turkey)

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ABSTRACT

A typical Seljukian town of Ahlat, located between the north-western shores of the Lake Van and the Nemrud and Suphan volcanoes of the Eastern Turkey is hosting rich and colorful cultural heritage sites. Among these, famous Seljukian Cemetery is a major archeological district with monumental tombstones (stelae). Excessive deterioration, erosion and lichen colonization can be observed in these cultural artifacts. The main objective of this study is the investigation of stones' physical characterization and evaluation of the microstructural features. A degradation model was outlined starting with the capillary water uptake from the bottom section and lichen colonization starting from the top and covering these tombstones upto their mid sections. This article provides some information about the historical town of Ahlat and its tombstones. Some physical and microstructural characterization of the gravestones and the results of chemical and physical analysis are also presented along with some recommendations.

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physical properties;
tombstones

1. Introduction

The town of Ahlat is located on the shores of Lake Van in Eastern Turkey and is approximately 60 km from the City of Bitlis (see maps in Figure 1). Ahlat has a population of approximately 37,000 according to official 2011 census. Being a truly historical site and on the path of the famous Silk Road (the ancient trading route from China to Europe), the town contains a variety of archeological monuments dating back to the Urartu Civilization of 1100 BCE (in some claims, it may date back to the Hurris in 4000 BCE) and to other, more recent, civilizations such as the Seljukians and the Ottomans (11th–17th centuries). The town was used by the Seljukians as a base for the Turkish migration into the Anatolian Peninsula (this historical event is known for the massive migration of nomadic Turkish tribes from Iran and Asia, starting during the 10th century and continuing throughout the following centuries). It was also used as a base for the campaigns of the famous Seljukian commander Alparslan and his troops following the Battle of Malazgirt (Manzikert) in 1071 AD. A confederation of Turkish tribes constituted the Anatolian Seljukian Central State. In this regard, Ahlat was a major Seljukian province, hosting rich historical buildings such as mosques, cupolas (vaults), graves, bridges, baths, and aqueducts spread all

over the region. One of the major historic sites in the town is the “Seljukian Cemetery,” which spreads over 200 acres and is located between the İkkubbe neighborhood and the Harabashir district. This graveyard hosts tombstones (stelae) of different shapes adorned with figures, motives, inscriptions (verses from the Quran, poems, local proverbs, and others), and ornaments, which date from early 12th–16th century (Çelebi 2001). Being in the candidate and temporary lists of UNESCO's Human Heritage sites, the graveyard has now been redesignated as a national park and there are more than 1,000 coffer tombs (some claim around 6,000 including many still under the ground), with or without tombstones, each displaying the properties of monuments (stelae) (Figure 2). These gravestones are mostly rectangular and have varying dimensions: width, 40–70 cm and height, 1–5 m (the height of the stele reflected the status of the deceased).

The stone used for these stelae is an ignimbrite, locally named “the Ahlat Stone,” which, being the best local construction material, has been used for centuries, and the associated master craftsmanship is still designated in the province as the “Ahlat Stone-mastership.” Ignimbrite is a volcanic pyroclastic rock produced during volcanic eruptions under very high gas pressures and temperatures. It should be noted that the Ahlat

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Figure 1. Geographical location of the Ahlat Town near the Lake Van of Eastern Turkey.



Figure 2. A View of Seljukian tombstones (stelae) in Ahlat.

region is also host to two important volcanic mountains: the Suphan and the Nemrud. The Nemrud, west of Ahlat, is a well-known volcano, about 3050 m high, and its last eruption, recorded in 1441, is regarded as insignificant in scale (source: <http://www.csb.gov.tr/db/>

[ced/editoridosya/bitlis_icdr2011.pdf](http://www.csb.gov.tr/db/ced/editoridosya/bitlis_icdr2011.pdf)). Ignimbrite, as a construction material, is one of the most commonly used and preferred natural building stones owing to its lightness, and ease of processing and shaping. It is very soft in its natural state, but hardens and gains strength and durability over time when exposed to atmospheric conditions, i.e., oxidation. Therefore, the stone can easily be processed, shaped, and crafted into ornamental figures, letters, inscriptions, motives, and other desired forms. Crafting and carving of ignimbrite can be done by hand (or more recently by machine, i.e., wire sawing) after it has been mined. Ahlat Stone is still used as the main construction and cladding-cover material in various constructions in the region such as dwellings, bath-houses, government buildings, and mosques. The Graveyard Stelae are various colors such as reddish-brown, dark brown (chestnut), and ash. Nowadays, the dark brown stones are widely used in construction and building in the region.

These monuments (both gravestone “stelae” and cupola “vaults”) have not been analyzed and evaluated for preservation up to now. There is serious structural deterioration, erosion, and deformation, which can be observed on the surface of the stones, along with excessive lichen colonization, which starts from the top and partly penetrates the mid-sections of the stelae causing extensive deterioration and discoloration (typically light yellow and light brown) on the surface of the tombstones (Figure 3).

The main objective of this study was to investigate the microstructural features and conduct physical and chemical analysis on a limited number of gravestone samples dating back to early 12th century. The samples have been exposed to very harsh environmental conditions with various threats of structural erosion and deterioration over the centuries. Microstructural evaluation and characterization were conducted on the samples and the results of the physical and chemical analysis are presented, along with some suggestions and recommendations. In this regard, detailed microstructural and physical studies should be used to facilitate the protection, restoration, and structural rehabilitation of these monuments, according to the standards and regulations of the preservation of cultural heritage, with the objective of preserving them for and transferring them to future generations.

2. Cultural significance of the town of Ahlat and the Seljukian Graveyard

The Seljukian Graveyard of Ahlat is the largest historical cemetery (200,000 m²) in the Islamic world (and one of the three largest cemeteries in the world) reflecting more



Figure 3. Structural deterioration, erosion at the center, and light yellow lichen formation starting at the top on the historical Seljukian gravestones of Ahlat.

than 800 years of Turkish art and cultural heritage. Nowadays, the Graveyard resembles an impressive open-air museum with more than 6,000 tombstones. Tombstones in the graveyard show very high-quality artistic values and exquisite carved designs and craftsmanship (Karamağralı 2002). Nomadic Turkish tribes brought these stele-type tombstones and graveyard culture during their massive migration into the Anatolian Peninsula from the Central Asian steppes. As a matter of fact, these gravestones are nowadays called “the Anatolian

Orkhon Monuments” due to the resemblance to the Gokturkian Orkhon Monuments located in today’s Mongolia. The widely known “The Orkhon Inscriptions” are monuments erected by the Gokturks in the early 8th Century in the Orkhon Valley in Mongolia. These inscriptions are considered to be one of the very first Turkish constructions and the inscriptions relate to the legendary origins of the Turks (Figure 4).

On the surfaces of the Ahlat stelae, biographies of the deceased, Quranic death verses, poems, local



Figure 4. (left) A view of the Ahlat stelae, and (right) a view of the Orkhon Inscriptions.

proverbs, and the name of the artist, along with highly symmetrical geometrical forms and figures with complex shapes, motives, and ornaments, were exquisitely carved by the craftsmen of Ahlat (Kanbarova 2015).

3. Site description and climate characterization

The environment has very harsh seasonal conditions with considerable temperature differences both in winter and summer (Table 1). Lake Van is the largest lake in Turkey, located in the far east of the country in the Van city district on a high plateau, 1648 m above sea level. It is the fourth largest endorheic lake (having no outlet) and the largest soda lake on earth, having a volume of 607 km³, area of 3570 km², and a maximum depth of 450 m (Çagatay et al. 2014). Lake Van has a unique environmental characteristics influenced by seasonal changes; in winter, the changes occur due to the position of the westerly jet stream and in summer, by extension of a subtropical high-pressure belt (Kwiecien et al. 2014). The lake water is characterized by high salinity and exceptionally high pH (S 22 g/kg, pH ~10), its chemical composition is dominated in equal amounts by sodium chloride and sodium carbonate and its concentration of carbonate species is about 65 times higher than seawater (Tomonaga et al, 2012). Being a saline soda lake, the deterioration of the exposed stelae may also be enhanced by salt and ice crystallization, due to water freezing in the stone's pores and capillary structure during the long winter season. Microbiological growth of algae, lichen films, fungi, and bacteria is another contributing factor to the decay of the stones.

The maps given in Figure 1 show the geographical location of Lake Van and the town of Ahlat. Some of the average weather parameters for Ahlat and its surroundings are given in Table 1. The climate is described as warm and temperate. In winter, there is much more rainfall than in summer. According to the Köppen-Geiger Classification,

the regional climate is classified as Csb (<http://www.van.climatemps.com/>). The average annual temperature in Ahlat, based on 30 years of weather data, is approximately 9°C. The average annual rainfall, based on 40 years of weather data, is 605.3 mm.

Most precipitation falls during spring, in April, with an average of 93 mm, while the driest month is July with 7 mm. The warmest month of the year is also July, with an average temperature of 21.2°C. In January, the average temperature is -2.7°C, the lowest average temperature of the whole year. The difference between the annual monthly minimum and maximum temperature is approximately 10–11°C. The largest temperature differences occur in January, which has an average precipitation of 59 mm. The difference in precipitation between the driest and wettest months is about 86 mm. The average temperature varies during the year by 23.9°C. Based on local statistics, the annual number of rainy days is approximately 94, with 30 days of snowfall. From November to March, the number of days below freezing point ranges between 14 and 24. The average snowfall height can reach up to 130 cm (source: www.ahlat.bel.tr). Humidity data show the highest average morning humidity during March and April at 82% but there are considerable discrepancies between average morning and average afternoon humidity values (e.g., average afternoon humidity values for March and April are typically 68% and 65%, respectively). Average annual wind speed for the Ahlat region is 6 km/h.

4. Materials and methods

4.1. Material description and characterization

An area of approximately 1,089 km² is covered by the outflow sheets of the Nemrud pyroclastics, which include three fallout units and an ignimbrite flow unit. This ignimbrite flow unit, called the “Nemrud Ignimbrite,” is

Table 1. Average monthly climatic conditions of the town of Ahlat.

Months	Precipitation, mm	Temperature, °C		Average Dew Point, °C	Average Morning Humidity, %	Average Afternoon Humid, %	Days with below freezing
		Low	Max				
January	59	-5.7	8.3	-8	78	70	30
February	72	-5.2	1.1	-7	78	71	27
March	76	-2.4	4.9	-3	82	68	24
April	93	2.6	11.6	2	82	65	7
May	74	6.6	17.1	6	78	61	-
June	30	10.4	23.1	9	70	54	-
July	7	14.5	28	12	61	54	-
August	7	14.4	27.9	11	61	53	-
September	14	10.7	23.7	8	62	51	-
October	69	5.4	16.1	4	74	56	1
November	77	0.6	8.8	1	80	65	14
December	60	-3.2	3.3	-5	77	68	27

Sources: en.climate-data.org/location/15409 and <http://www.myforecast.com/bin/climate.m?city=75771&metric=true>

the largest product of the volcano and covers the landscape in the vicinity of Lake Van, the city of Bitlis, and the town of Ahlat. Ignimbrites are highly heterogeneous pyroclastic rocks, containing volcanic glass, high amounts of pumice, and lithic fragments and particles. It has been reported that approximately 100 km³ of this pyroclastic material flowed under gravity and high temperatures from the Quaternary Nemrud stratovolcano, which has an elevation of 2950 m above the sea-level and a base area of approximately 210 km² (Şimşek and Erdal 2004). Its caldera is 7–8 km in diameter. Based upon the eruptive characteristics of the Nemrud, the evolution of the volcano is classified into three main stages: pre-caldera, syn-caldera, and post-caldera. The Nemrud ignimbrite was the most voluminous product of the volcano and spread in all directions, along with Plinian fallout, after the explosive eruptions during the pre-caldera stage. Welded Nemrud ignimbrite is a single flow unit exhibiting a varying degree of welding and consolidation due to local conditions. A variety of colors from black, dark gray, and dark brown to light brown, reddish, and pale yellow can be observed in different quarries (Ulusoy et al. 2012). The study by Ulusoy et al. on the volcanic evolution may explain the varying quality of the ignimbrite blocks used in the graveyard (dense welding and consolidation, texture, and fiamme structures).

Ignimbrite blocks have been mined, cut into large slabs, and used as a major construction material for thousands of years, starting in the period of the Uartian civilization and extending all the way through to the Seljukian and Ottoman dominance in the region. Based on varying color, texture, and structural features, three different types of ignimbrite have been identified in different levels of the deposit. The reddish-brown colored ignimbrite blocks are poorly-to-moderately welded (Çubukçu et al. 2012; Ozvan et al. 2015). Tombstones used in the Seljukian Graveyard were most probably carved from these poorly welded reddish-brown ignimbrites due to the ease of their shaping and crafting. Moderately and strongly welded ignimbrites were used extensively as construction materials in other historical buildings such as castles, mosques, caravanserais, bath-houses, dwellings, and other buildings. In a study by Calcaterra et al. (2004), Campanian ignimbrite, used in medieval architecture, was investigated using in-depth analysis and characterization of the stones. Ease of workability and widespread occurrence was mentioned, along with its good technical features and use as the most sought-after building stone in the Campanian district, as in the case of the Ahlat stone. The most widespread decay in these structures is listed as lacks, alveolization, and biological patina

(from lichen colonization as in the Ahlat Stones). The microstructural analysis revealed that feldspar, in amounts ranging between 91–95%, was the most abundant phase.

In other relevant works (Ozvan et al. 2015; Şimşek and Erdal 2004), various types of freshly mined Ahlat Stone were investigated as construction materials, and some of the mechanical and physical properties of the ignimbrite rocks in the region were measured and reported (see Table 5). The parameters determined in these investigations included petrographic, geochemical, compressive strength, capillary water absorption, flexural strength, and abrasion loss. The reddish-brown and dark brown ignimbrites investigated in one of the recent studies were claimed to have been used in the construction of the Seljukian gravestones (Ozvan et al. 2015). Such recent investigations have great relevance to the evaluation of the historical materials and some of this data is included in the discussion and in the condition assessment of the Seljukian stelae. Recently mined ignimbrites (reddish- and dark brown) contain plagioclase, sanidine, hornblende, volcanic glass, opaque minerals, and lithic fragments. The ratio of lithic fragments, which are similar to obsidian, trachyte, and rhyolite, is 13–17%. These ignimbrites have poorly to moderately welded microstructures (Ozvan et al. 2015). The capillary water absorption potentials of different ignimbrites from the Ahlat region have also been investigated and compared with other natural stones extracted from neighboring regions (Dinçer et al. 2012; Ozvan et al. 2015). These studies also dealt with the Ahlat Stone as a construction material, and the capillary water absorption data is therefore relevant to determine the deterioration mechanism within the material. Based upon the test results, it is claimed that significant physical deterioration may occur around the stone surfaces of buildings in contact with water. Moreover, significant relationships were also determined between the capillarity values and physico-mechanical properties of the samples. In another relevant work concerning the Ahlat region (Okuyucu and Erdil 2009), the seismic performance evaluation of the Emir Bayındır Cupola (built using reddish-brown colored ignimbrite stones from the region and located close to the Ahlat Cemetery) was investigated and some relevant data was provided on the stone's material properties, deterioration, and cracking. There are additional relevant studies concerning weathered tuffs and the deterioration of different materials, including ignimbrites, from different regions of Central Anatolia (Korkanç 2013; Topal and Doyuran 1998; Topal 2002; Topal and Sözmen 2003).

For this study, a limited amount of very small samples (due to the regulations) were taken from the districts under the supervision of the regional staff of the Ministry of Culture and Tourism and the Municipal

Government of Ahlat. Samples were carefully extracted from various sites, specifically from the broken fragments of stelae representing those with the most deterioration, erosion, and biofouling problems. Samples were classified based on their size and location of the structure. Relatively large fragmented samples were coded as the “Ahlat Stone-block” and others extracted just beneath the lichen covered surfaces as the “Ahlat Stone-surface.”

Microstructural examination of the samples revealed typical features containing plagioclase, sanidine, hornblende, volcanic glass, opaque minerals, and lithic fragments (Figure 11) similar to that of the recent study by Ozvan et al. 2015. However, the degree of welding is quite different from that of freshly-mined ignimbrite and distinctly poorer welding (i.e., loosely bound fragments) is apparent in all samples due to the effects of time i.e., more than 600–800 years.

4.2. Methods

The following methods and techniques were employed for the physical and microstructural characterization of the samples taken from the graveyard district.

- (1) *Qualitative mineralogical phase analysis, XRD (X-Ray Diffraction techniques)*: Qualitative mineralogical phase analysis was carried out using a Shimadzu XRD-6000 unit with a Cu X-ray tube ($\alpha=1.5405$ Angstrom).
- (2) *Semi-Quantitative elemental analysis, XRF (X-ray Fluorescence techniques)*: Semi-quantitative elemental analysis was carried out using a Philips PW-2404 model wavelength dispersion X-ray fluorescence unit.
- (3) *Optical microscopy techniques*: Samples were prepared according to the standard metallographic techniques for optical microscopy (ASTM E3-95 Standard Practice for Preparation of Metallographic Specimens, approved May 01, 2011).
- (4) *SEM-Scanning Electron Microscopy techniques (including elemental analysis)*: Microstructural analysis was conducted using SEM-Scanning Electron Microscopy (Jeol- JSM 6335F) techniques.
- (5) *Density, Water Absorption (%), Porosity (%) Measurements*: Bulk density, water absorption (%), apparent porosity (%) measurements were carried out according to the standart methods (EN ISO 10543-3: Determination of water absorption, apparent porosity, apparent relative density and bulk density. Approved July 1997).

- (6) *Thermal expansion coefficient determination*: Thermal expansion coefficient measurements were performed using a Netsch DIL 402C Dilatometer Unit.

5. Results and discussion

5.1. Chemical and mineralogical analysis

Table 2 shows the results of this study in percentage oxide content, along with the data given in the studies on recently extracted Ahlat Stone by Şimşek and Erdal 2004 and Ozvan et al. 2015. The results do not indicate distinct differences in the oxide contents with the exception of the alkali element Na₂O. There is roughly a 50% decrease in percentage Na₂O content between recently-extracted stones and the historical Ahlat gravestone samples. The very high salt content of Lake Van (S 22 g/kg) and its proximity to the graveyard is the reason for such a decrease in Na₂O percentage. When plotted on the total alkali (Na₂O + K₂O) vs. silica (SiO₂) classification diagram (TAS-Total Alkali Silica) (Le Maitre 1984), samples from the stelae were in the alkali trachyte/trachyte field, as was the case in the relevant studies of Şimşek and Erdal (2004) and Ozvan et al. (2015). Similarly, based on the SiO₂ vs K₂O and Na₂O vs K₂O diagrams, the stelae samples fall in the “High K-Series” and “Shostonic Series” fields.

The results of the qualitative mineralogical phase analysis on the historical Ahlat gravestone samples are given in Table 3.

XRD analysis of the “Ahlat Block” sample revealed feldspar (k-feldspar and plagioclase feldspar found in SEM elemental analysis), magnetite, and an amorphous phase present in the stone’s structure. No spectrum peak for clays was found in the “Ahlat Block” samples. XRD analysis of the “Ahlat Surface” samples, on the other hand, indicated the presence of quartz and illite phases in addition to feldspar and magnetite. The occurrence of clays, quartz, and illite along with

Table 2. Elemental analysis of the samples of historical Ahlat gravestones and the data for the recently extracted Ahlat stones.

Oxide content %	Historical Ahlat Grave Stone		Original, unprocessed, recently extracted Ahlat stone (Şimşek et al 2004)	Original, unprocessed, recently extracted Ahlat stone (Özvan et al. 2015)	
	Ahlat Block4	Ahlat Surface1		N1	N2
Al ₂ O ₃	17.925	17.19	15.33	16.03	15.53
CaO	1.706	1.506	2.00	1.45	1.46
Fe ₂ O ₃	5.017	4.795	4.90	4.47	4.49
K ₂ O	5.400	5.257	4.81	5.11	5.11
MgO	0.555	0.431	0.53	0.21	0.20
Na ₂ O	2.695	3.191	5.46	5.90	5.85
SiO ₂	65.361	66.397	64.05	66.25	66.80
TiO ₂	0.434	0.389	0.42	0.40	0.38

Table 3. Qualitative mineralogical phase analysis on the same historical Ahlat gravestone samples.

Sample codes	Elements
Ahlat Block No.4	Feldspar Magnetite, Fe3O4; (Powder Diffraction File (PDF) No: 19–629) Amorphous phase
Ahlat Surface No.1	Feldspar Magnetite, Fe3O4 (Powder Diffraction File (PDF) No: 19–629) Amorphous phase (PDF No:46–1045) Illite (K,H ₃ O)Al ₂ Si ₃ AlO ₁₀ (OH) ₂ (PDF No:26–911)
Ahlat Surface No.2	Feldspar Magnetite, Fe3O4 (Powder Diffraction File (PDF) No: 19–629) Amorphous phase Quartz, SiO ₂ (PDF No:46–1045)

amorphous phases indicates a typical chemical weathering environment, the products resulting from mineral dissolution and/or chemical actions of lichens on the surface (Chen, Blume, and Beyer 2000).

5.2. Characterization of decay features

Table 4 shows the following basic weathering mechanisms acting on the historical Ahlat steale: spalling/flaking, mechanical erosion, material dissolution, water and gas absorption, freeze-thaw, hydration, and precipitation. The moisture content and its distribution and the presence of saline solutions that remain a long time within porous media of stone materials, intensify weathering processes such as those mentioned above. (Martinho et al. 2014).

5.2.1. Physical and chemical weathering and decay features

Table 5 shows the results of the density, porosity, and water absorption (under atmospheric pressure) investigations carried out on the Ahlat Stone-block samples. As the Ahlat Stone-surface samples were smaller in size, measurements of density, porosity, and water absorption could not be determined. Table 5 shows that the porosity levels and

Table 5. The results of density, porosity and water absorption measurements for the historical Ahlat Stones along with the average values given in the studies of (Şimşek and Erdal 2004) and Özvan et al., 2015 on recently extracted Ahlat ignimbrite.

Sample code	Type	Density, gm/cc	Porosity %	Water absorption %
Block4/1	Ahlat	1.25		40.58
Block4/2	Ahlat	1.30	48.48	37.20
Sample Şimşek et al	Ahlat	1.89	27.27	25.1
Sample Özvan et al	Ahlat	1.51	28.89	18.68
		1.57	27.40	16.92

water absorption values of the historical Ahlat Stone samples are considerably higher, 50% and 37–40%, respectively, than those of recently-extracted stones, with average porosity values of 27–28% and 17–25% water absorption, indicating that exposure to the natural environment over the centuries has greatly changed the stone's structure. The porosity level (pore size and distribution) and capillary water absorption show a very close correlation, causing extensive moisture expansion into the stone and affecting the structure by internal weathering (Wedekind et al. 2013).

Whenever a porous structure such as the Nemrut ignimbrite is in contact with water, instantaneous water absorption occurs due to its capillary microstructure and water rises from the bottom immersed section toward the upper portions, depending on the porosity level (pore size, pore size distribution, and channels in between the pores) and the capillary water absorption characteristics. Capillary water absorption constants for the Nemrud ignimbrite were measured between 187.31–821.87 g/m² s^{0.5}. Based on such high values, the Nemrud ignimbrites are classified as “high absorbing rocks” (Dinçer et al. 2012). As well as the environmental conditions at the site, structure specific parameters, like water capillarity, absorption, porosity, and permeability strongly influence deterioration and decay of the stones. The capillary water absorption potential of different ignimbrite materials from the Ahlat region was

Table 4. Basic weathering mechanisms on the Ahlat Stelae.

Type of process	Mechanisms	Explanation
Physical Weathering	Thermal expansion-contraction	Spalling and flaking seem to be major causes in the middle sections of stelae due to constant structural variations of expansion and contraction by the temperature difference of approximately 10–11 °C.
	Freeze-thaw (frost disintegration)	Freeze-thaw may not be an important mechanism acting on the stelae.
	Salt crystallization	Decrease in Na ₂ O % would be the indication of salt crystallization due to very high salt content of the Lake Van (about 65 times higher than in seawater, S 22 g/kg) just nearby the graveyard.
Chemical Weathering	Moisture	Capillary water uptake due to high absorbing structure
	Mechanical erosion	Spalling/flaking and fragmentation at the mid-sections.
	Hydration	Not investigated.
Biological Weathering	Oxidation	Not investigated.
	Dissolution /chemical erosion	Amorphous phase and illite and quartz on the surface indicate mineral dissolution process.
	Microorganisms	Fungi formation and lichen colonization

investigated (Dınçer et al. 2012; Ozvan et al. 2015) and compared with other natural stones extracted from the neighboring regions. Based upon the results, it is claimed that significant physical deterioration may occur around the stone surfaces of buildings in contact with water. Moreover, significant relationships were determined between the capillarity values of samples and their physico-mechanical properties.

As known, water is a most aggressive substance, and acts as a vehicle for weathering processes. The water absorption of the stelae is measured at 37–41%.

The photomicrograph given in Figure 5 shows pores with dimensions of 96–207 μm. Even though a detailed pore size and distribution analysis was not conducted on the samples, the pores within the interior section of stelae can be considered as “mesopores,” as in the case of the recently-quarried samples studied by Ozvan et al. 2015. Therefore, water capillarity is the major driving force, drawing water from the bottom section then expanding and distributing it toward the central portion of the structure. In this regard, the main mechanism of physical degradation, starting from the bottom up to the middle, is effective water capillary suction through the pores and channels in the structure.

The thermal expansion coefficient was measured at

$$T\alpha = 7.02 - 7.14 \times 10^{-6} 1/K$$

which approximates to a typical value for clay structures (McKinstry 1965).

During field observations, fragmentation due to crack formation and/or crack propagation was not observed due to the highly porous structure of the tombstones. The microstructural features of the Ahlat ignimbrite exhibit a highly porous and composite structure that combines light weight and stiffness. Hard pieces and particles of feldspar and opaque minerals, distributed in soft pumicious matrix along with pores, can deflect crack path and act as crack inhibitors. Such unique natural microstructures, as in the Nemrud ignimbrites, attract the interest of material designers due to their porous nature and tough architecture (Wegst et al. 2015). Many of the microcracks occur due to thermal expansion and contraction during the daily cycle of atmospheric heating and cooling. Mesopores and hard blocks and pieces of unevenly distributed 100–150 μm grains of K-feldspar, plagioclase feldspar, magnetite, and other opaque minerals act as barriers to microcrack propagation. But spalling and flaking seem to be major causes of failure in the stelae middle sections due to constant structural variation resulting from expansion and contraction caused by the 10–11°C temperature difference. Based on field

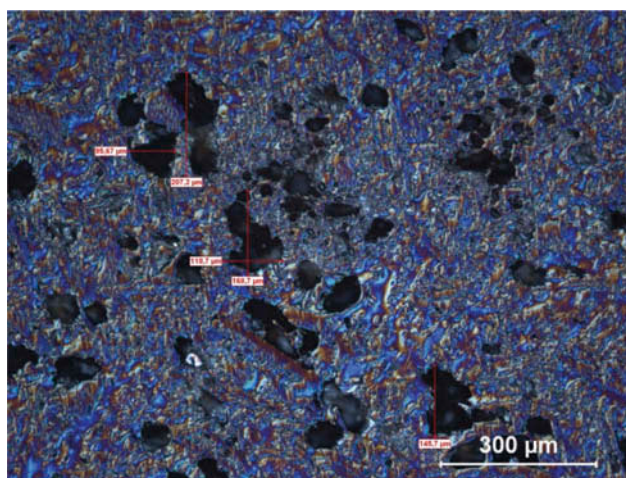


Figure 5. Optical photomicrostructure showing pores in the interior section.

observations in the graveyard, many tombstones had broken from the mid-section. Ozvan reported that 941 tombstones were broken approximately 60–70 cm from ground level (Ozvan et al. 2015). This level, as the critical damage section, corresponds the mid-section of the stele, and deterioration due to spalling/flaking and erosion leads to eventual breaking and fragmentation of the structure.

As discussed, the XRD analysis on the “Ahlat-surface” samples indicated the presence of amorphous phase along with quartz and illite. In this regard, the typical chemical weathering mechanisms, due to mineral dissolution, need to be investigated as another decay process along with the chemical action of the surface lichens.

5.2.2. Biological weathering and decay features

The view of the Ahlat Seljukian Graveyard, given in Figure 6, shows eight stelae along with a cupola (vault) at the far end of the view. Discoloration (light grayish color) due to lichen colonization of less than 50% of the surfaces starts at the top and descends toward the central section. In some stelae lichen cover more than 50% of the surface. As mentioned, in most cases spalling/flaking and erosion are observed in the mid-sections of stelae. In this regard, the deterioration and decay of the stones is due to complex mechanisms, simply outlined in Figure 7, including lichen colonization on the upper sections, spalling-erosion in the mid-sections, and capillary water/moisture effects starting from the bottom section.

In the cemetery it can be seen that while some stelae are in good condition, others exhibit considerable erosion and degradation. The graveyard is wide-open and shading is very limited with very few trees present. Therefore, sun exposure is somehow very homogeneous throughout the



Figure 6. A view of several Ahlat Seljukian stelae. Lichen coverage in lightly colored portions starts from the top and penetrates to mid-sections.

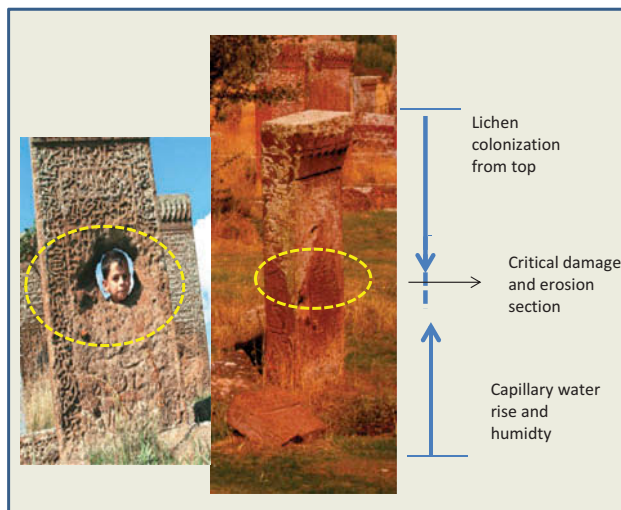


Figure 7. Degradation model of the stelae: Lichen coverage in lightly colored portions starts from the top and penetrates towards the center and capillary water uptake towards the centre.

whole graveyard. As pointed out, the height of a stela was a demonstration of the status of the deceased, and most of the taller stelae are in better condition; possibly better quality stones were used for carving the motives and inscriptions (Figure 4 left). In this regard, one may also argue that lesser quality stones were used for the lower class and therefore their gravestones have degraded more than the others. The stones used in the graveyard were brought from different mines in the region, which may also explain the difference in the degradation mechanisms.

Major causes of deterioration and the general condition of the stelae can be described and classified as follows.

- The lichen colonization and penetration (typically light gray/yellow and light brown colored layers) starting from the top and descending towards the central section.
- Capillary water absorption and moisture uptake approximately 25–60 cm from the ground to the central portion. There is no lichen coverage in these sections.
- Typically eroded and spalled surfaces at the center were observed in most of the stelae (critical damage and erosion section). The erosion and due spalling/flaking in this section is severe, and concave grooves, cratering, and eventual hole formation are detected in some stelae. Field observations revealed that most of the gravestones broke from these central locations (Figures 7 and 8).

A close inspection of the surfaces of the stelae indicates this complex, multiple mechanism of deterioration and decay of the structural integrity. Each stela is covered from the top with lichen-fungi formations which diffuse towards the mid-section, and exhibit a variety of typical lichen colors (light gray/yellow and light brown). Most of the stelae exhibit a typical spalled-eroded concave groove and/or hole at the mid-section (approximately 25–60 cm from the ground). Folktales in the town explain that these holes and grooves are due to shell impacts of the Russian Army artillery that invaded the town for a very short time in 1916. Surely, this cannot be true as the hole formation is symmetrical (same conical grooves on both sides) and shattering and fragmentation from impact is not seen on the surfaces of the stelae. The big hole in the central section of the stela (Figure 7 (left)) is too large for the folktale to be true. However, the series of stelae in Figure 8 shows that the central sections with certain erosive features already in progress. Perhaps, a low quality stone might degrade faster and a large hole develop over time.

Being just a folktale and an exaggerated rumor it is, however, it is interesting to note that almost every single hole in the center of stelae is in the approximate identical location, indicating the capillary water level; there is no lichen coverage on these mid-sections. In addition, this central section also indicates the snow layer that remains for months during the winter. Climatic data, given in Table 1, indicates that around 130 days per year are below freezing point, the annual number of snow days is approximately 30 and snowfall is 30 days. The average snowfall height can reach 130 cm (source: www.ahlat.bel.tr). Cyclic freezing and melting of water carrying soluble substances (note



Figure 8. Eroded central sections of some stelae.

again the salinity, alkalinity and proximity of Lake Van water (Glombitza et al. 2013)) through the pores, voids, and capillaries causes efflorescence on the surface and probable ice- and salt-induced spalling. Such a repeat freeze-thaw process and frost damage caused the weak central sites of the high-porosity (approximately 50%) stelae to erode and crater at this particular position over time.

The major lichen types on the Seljukian tombstones are “*Lecanora muralis*” (pale green) and “*Candelariella*” (yellowish-orange). These lichens are the most common types covering the historical buildings (Ozvan et al. 2015). Other than the possible anthropogenic effects in the region, environmental effects from Lake Van bring a variety of particles, including carbonaceous and organic species (Huguet et al. 2011), due to the moderate winds (average wind speed in the Ahlat region is 6 km/h for all months of the year).

A carefully prepared sample representing a cross-section of a typical stele surface, starting with the lichen coverage and following its roots toward the interior, was examined using SEM techniques. In Figure 9, the overall microstructural view of such sample is given and the structure is classified based upon the features as follows.

- (1) Main Interior Region
- (2) Lichen Thallus-Roots Region
- (3) Lichen-Surface Region

The cross-sectional area of the lichen-covered surface is approximately 5–7 μm deep through the interior mass of the stele. A complex and tangled network of lichen thallus-roots is observed underneath the surface and reaches more than 4–5 μm into the main body.

Biodeterioration from lichen formation, growth, and penetration deep into the microstructure might be considered to be the other major factor determining the

stelae decay, with a reservation suggesting the protective role of the lichen colonization. Extensive thallus penetration and the consequent network produced in the interior may provide a structural integrity to the surface. Another major problem for these stelae seems to be lichen layers filling in the finely and exquisitely carved ornaments, motives and inscriptions. Before deciding on the method of preservation and restoration, it is important to investigate the full characteristics of the lichens (formation, growth, and penetration) on the Ahlat stelae. The type of lichen, algae, and fungal formations, along with bacteria and other microorganisms, rate of growth, and resulting decay and/or protective role should be evaluated extensively. It is seen that the lichens covering the surface here are endolithic and that the thallus is completely immersed and penetrates deep into the substrate using pores, capillaries, cavities, and grain boundaries as pathways, Figure 10 (right).

A very porous microstructure (as measured 48–51%) with non-homogeneous grain size distribution is observed in the interior of the samples. It is obvious that the degree of welding is extremely poor and loosely bound grains constitute the structure. Unevenly distributed blocks of 100–150 μm K-feldspar, plagioclase feldspar, magnetite, and much finer grains of pumice, rock fragments, ash, and aggregates are seen as slightly-welded, separate, and loosely bound pieces throughout the microstructure. Mineralogical phase analysis indicates that some volcanic glass pieces also constitute the main matrix.

Figure 11 shows optical photomicrographs of the interior. Irregularly shaped, 400–600 μm long feldspar and opaque mineral grains, distributed unevenly through a pumicous matrix constituting of pumice, volcanic rock, and glass pieces, and tiny lightly colored areas, depict the porous microstructure. The feldspar grains are fractured into pieces and cracks can be

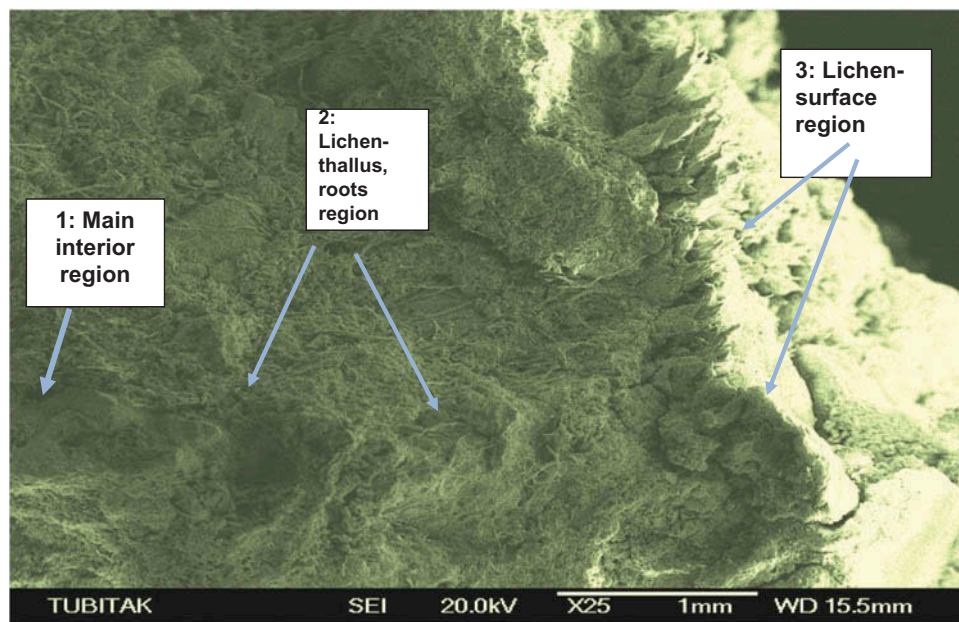


Figure 9. A typical general microstructural view of the sample collected from the historical Ahlat Seljukian Graveyard.

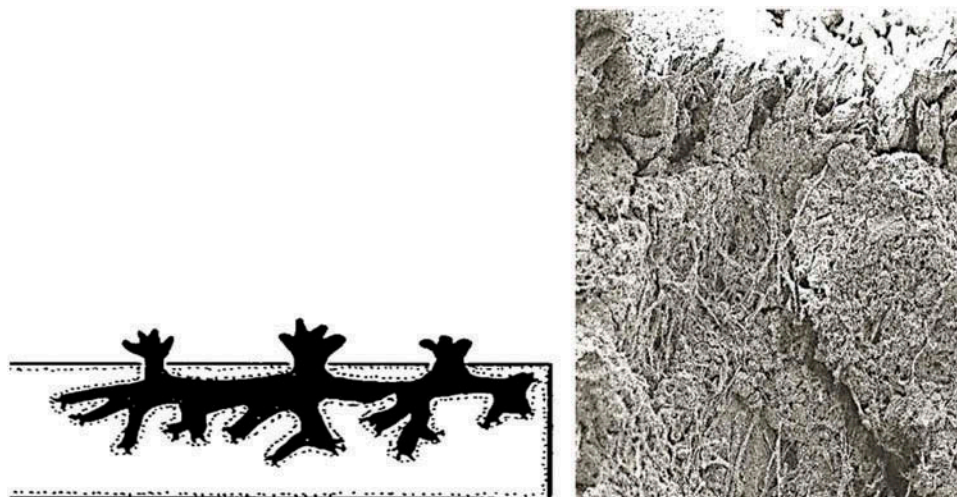


Figure 10. Left: Endolithic lichens based on the forms of growth of thalli sketched in Lisci et al. 2003. © Lisci et al. 2003. Reproduced by permission of Lisci et al. Permission to reuse must be obtained from the rightsholder.

Right: Cross sectional view of Lichen-surface showing the penetration of thalli in an Ahlat stele.

observed within these grains. Holes, 50–60 μ m wide, both inside the feldspar grains and on grain boundaries are also present throughout the structure. It is obvious that such a porous structure with open holes and wide capillaries acts as pathways for lichen roots i.e., thallus. On the other hand, it should be noted that, thanks to such high porosity and hard grains of feldspar distributed in soft pumicous matrix, no significant cracking occurs on the stelae due to temperature fluctuation during any seasonal changes.

Figures 12a and 12b show the microstructural features of the 2nd region of lichen thallus-roots with immersed

and elongated roots penetrating the grains and porosity sites. The SEM micrographs indicate a network of lichen-algae roots, deep in the structure, covering the grains and penetrating through the voids, pores, and channels. These roots were within a 2 mm thick evenly-covered area, some of them reaching 400–500 μ m in length. Considering the past centuries of exposure of the foundations of these stelae to environmental factors, the rate of growth for lichen roots-thallus is extremely slow and getting even slower as the stone ages, as indicated in the relevant literature (Beschel 1961). It should also be noted that lichens are used in the archaeological dating method

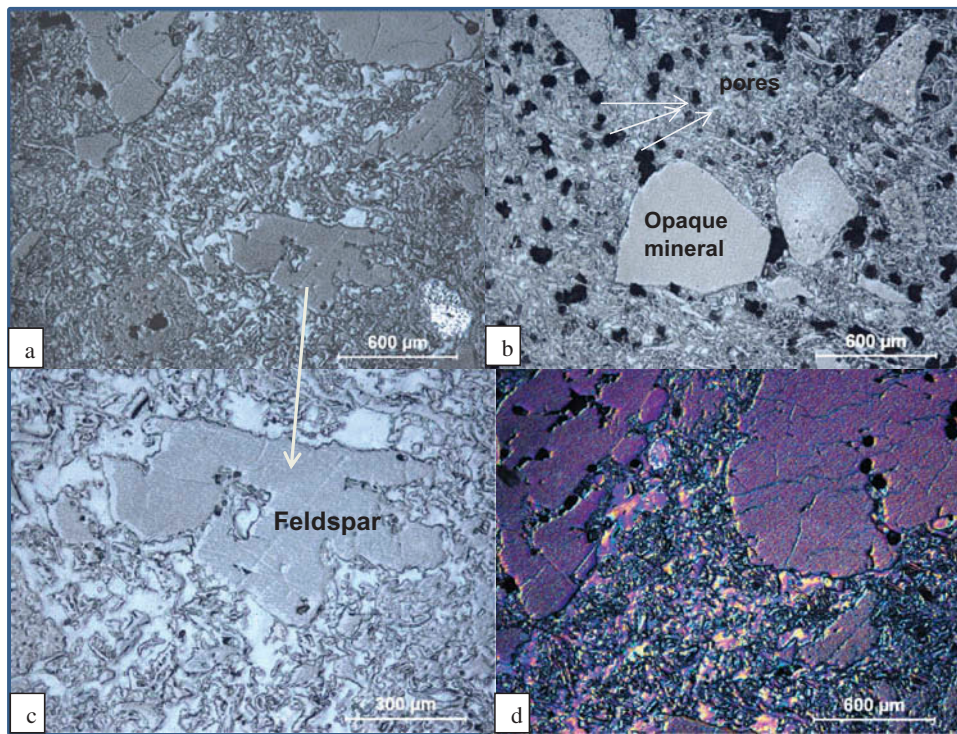


Figure 11. Optical photomicrostructural features of the interior region; large blocks of feldspar and opaque minerals are distributed within a very porous matrix. (a-c) parallel; (d) cross polarized light.

known as “lichenometrics”. Lichen thallus is known to grow at an extremely slow rate and a 4–5 mm depth of lichen diffusion into the substrate of the stelae indicates an approximate growth rate of 0.5–0.6 mikrometer/year. Presumably there has not been any mechanical cleaning and removal during the past 800–900 years. This is quite possible as graveyards are considered to be the holy places and intervening with tombs and tombstones is strictly forbidden in Eastern and Islamic cultures.

Lichen roots extensively covering the microstructure through pores, voids, cavities, and capillaries have resulted in an enlargement of grain boundaries and loosened the whole matrix. However, it is seen that

the strained thallus also acts as a binding fiber, holding the finely fragmented soft matrix together and protecting the structure from further disintegration.

Figure 13 shows such lichen root thallus penetration through the grains, pumicious matrix, and aggregates. Enlargement of voids and cavities between the grains and aggregates and the thallus forcing its way, growing, and extending toward the more porous path is distinctly demonstrated in this SEM micrograph. Overall entanglement of thallus with the grains and aggregates, and the resultant microstructure resembles a kind of moderate reinforcement among the grains, making the whole structure coherent, tough, and lasting. Lichen

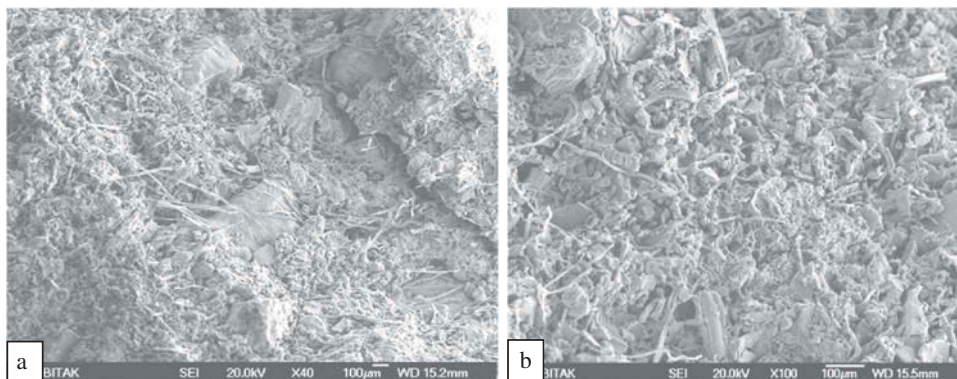


Figure 12. Micrographs of the 2nd Region of lichen roots.

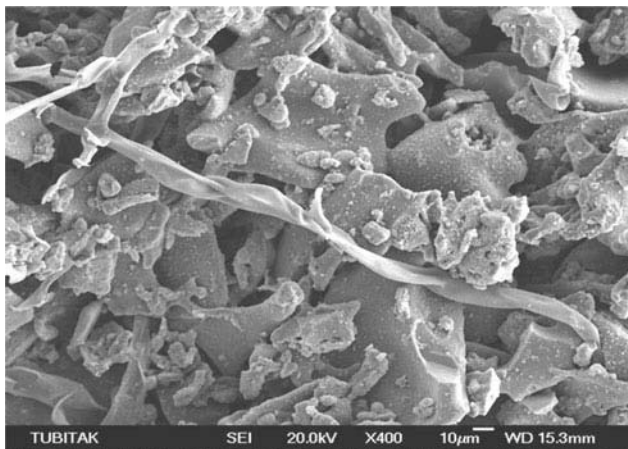


Figure 13. An enlarged SEM view revealing lichen penetration and loss of cohesion.

roots thallus, tangled through the pumiceous aggregates and feldspar grains, constitutes an array, and the fiber-like network acts as reinforcement, binding and stabilizing the matrix in a coherent form. Such binding and protective effects of endolithic hyphae on the surface of and within structures are also discussed elsewhere (Mc Ilroy de la Rosa, Warke, and Smith 2014; Pinna 2014).

There are continuing discussions on biological growths on stone and whether “it is a blessing or blight (Price and Doehne 2010).” While many organisms contribute to the deterioration of stone, in some cases bioorganisms, along with their colorful appearance, may act as a barrier and stabilize the surface from further decay. Therefore, it is claimed that the lichen coverage of the stone surface may be an inhibitor to further decay and deterioration. The tightened network of thallus surrounding the mineral particles stabilizes the structure and reduces weathering (Pinna 2014). Lichen coverage is then described as passive “umbrella” or “thalline shielding” in the bioprotection of colonized rock surfaces. Binding and protective effects of such thallus roots and dense surface covers, isolating the structure from a harsh environment, are also noted in other

investigations (Ariiio et al. 1995; Mc Ilroy de la Rosa et al. 2014). Therefore, elimination of lichens and removal of thallus may leave the surface in a more porous condition, and the structure may be exposed to more chemical attack. Thus, decay of the stone may be accelerated following any mechanical washing-cleaning procedures (Warcheid and Braams 2000; Mottershead and Lucas 2000). Pinna (2014) reported that lichen colonization controls the moisture in stones under harsh environments. Based on capillary water measurements, it was revealed that lichens protected the stone from rapid water uptake and did not significantly affect the mechanical properties. Such findings confirm the model outlined in Figure 7, where lichen coverage from the top to middle sections plays an important role in regulating the humidity caused by the water capillary suction from the bottom section, and stabilizes the integrity of the structure by regulating thermal transmission and water vapor diffusion (Pinna 2014). It should be noted that spalling-erosion and flaking on the lichen-free surfaces of the mid-sections verify this hypothesis. In this regard, lichen coverage on the stela may also provide a barrier or protective layer against wind, rain, snowfall, and may limit erosion on the upper sections.

The lichen surface region of a stele is seen in the SEM photomicrographs in Figure 14, showing a variety of bioorganisms, such as moss with leaves exceeding 500 µm in length, and a fungi-like appearance all over the surface. As for the preservation and conservation of lichen-covered stones, there is an ongoing debate as to whether cleaning and mechanical removal of lichens or leaving them as they are is the right direction. Lichen removal from tombstones, sculptures, and monuments is known to be practiced widely even though it can damage the structure. In most cases, the thallus forms a reinforcing network within the microstructure, and its removal may cause severe damage to the surface. Particularly for surfaces covered and colonized by endolithic lichens, mechanical cleaning is not favored since removal of the thallus leaves the surface highly

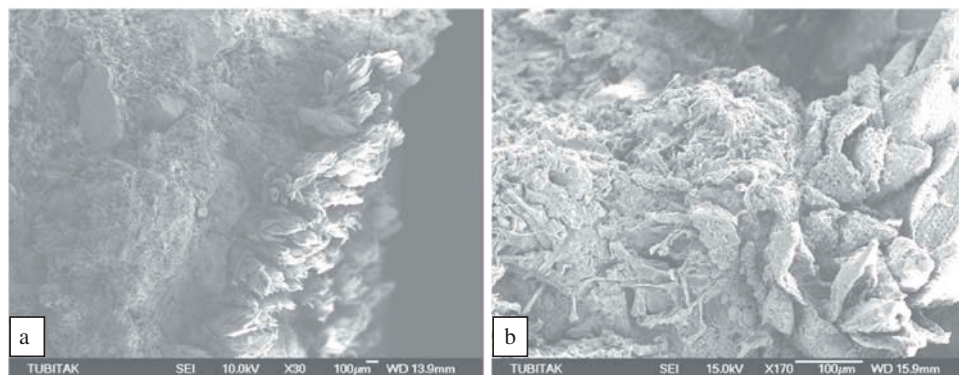


Figure 14. SEM photomicrograph of 3rd Region of lichen-surface interface starting from the surface.

porous and more open and vulnerable to environmental effects such as acids and moisture. (Lisci, Monte, and Pacini 2003). The SEM micrographs clearly demonstrate this fact and show a very porous microstructure and intact dangling grains and fragments. In this regard, minimal intervention should be considered until extensive in-depth investigation into the exact role and function of bioorganisms is fully understood and documented (Pinna 2014).

Full assessment should also be done to see if the lichens are acting as passive protective shields (or “umbrellas”) against the harsh environment of Ahlat and Lake Van. It is also known that there is an ongoing project on the mechanical cleaning of lichens from the Ahlat stelae, though not much information is available



Figure 15. A view of a stele recently cleaned. Left: Before the cleaning; Right: After the cleaning (Source: http://www.eskiahlatkazisi.com/foto_gallery/LIKEN%20TEMIZLIGI/default.htm). © Eskihlatkazisi.com. Reproduced by permission of Eskihlatkazisi.com. Permission to reuse must be obtained from the rightsholder.

yet (only a series of photos on the resulting mechanical cleaning of stones as given in Figures 15 and 16). The mechanical removal of 5–7 mm of lichen seems to uncover the finely carved surface of the stele and the exquisite craftsmanship reappears following such treatment (Figure 16). However, it should be kept in mind that these monuments are still in the same open atmosphere of Ahlat town and Lake Van, and are fully susceptible to lichen recolonization. In this sense, repeated cycles of mechanical removal of lichen layers might erase certain characteristics of the artistic appearance of the motifs, inscriptions, and ornamentation.

Once again, it should be underlined that precise decay and damage analysis and diagnosis are vital for the preservation and conservation of the Ahlat stelae. A comprehensive chemical and elemental analysis, testing and characterization, evaluation and assessment of the data are essential for the sustainable preservation of these beautiful cultural and historic artifacts. This present study should be considered as a preliminary work to shed some light on the characteristics of the Ahlat Stones and further detailed and systematic investigation should be initiated in due time.

6. Conclusions

Based on chemical and XRD-XRF analysis, physical measurements and microstructural evaluations, along with the field observations in the historical Seljukian Cemetery of Ahlat, Turkey, an overall condition assessment is outlined. Lying in a harsh environmental and subject to varied seasonal conditions for more than 800 years, the stelae are exposed to the effects of moisture, water capillary absorption, cyclic heat changes, and colonization by bioorganisms (lichen, fungi, and others). An overall descriptive model, depicting the condition of the stelae is proposed,



Figure 16. Cleaned surfaces of tombstones.

starting with the capillary water uptake from the bottom section moving toward the mid-section causing deterioration of the structure. Lichen colonization starting from the top and covering the stelae down to the mid-section is another mechanism that limits degradation and plays an important role in regulating moisture and acting as a protective layer against wind, rain, and other environmental factors. However, most of the stelae have severe flaking and fragmentation due to spalling-erosion in the mid-sections where there is no lichen coverage. Recent data (Ozvan et al. 2015) and our field observations reveal that most of the damaged and fragmented tombstones are broken-off at these mid-sections. An ongoing project on the Ahlat stelae on the mechanical removal of lichens and cleaning of the surface has uncovered finely carved surfaces and exquisite craftsmanship that reappears following such treatment. However, it should be kept in mind that these monuments are still in the same open atmosphere of Ahlat town and Lake Van and are fully susceptible to lichen recolonization. In this sense, the repeated cycles of mechanical removal of lichen layers might erase certain characteristics of the motifs, inscriptions, and ornamentation. Precise decay and damage analysis, and diagnosis are vital for the preservation and conservation of the Ahlat stelae. A comprehensive biological, chemical, and elemental analysis, testing and characterization, evaluation and assessment of the data are essential for the sustainable preservation of these beautiful culturally and historically important artifacts.

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