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Characteristics of the Weathering Zones Developed Within the Tuffs of the Midas Monument

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Abstract: The Midas monument, an impressive cult facade located in the southern part of the Eskişehir province in central Anatolia, Turkey, was made within tuffs (white and pink), which now have deterioration problems. In this study, the depth and characteristics of the weathering zones that have developed in the white and pink tuffs have been investigated through thin-section studies, X-ray powder diffractometry, methylene blue adsorption tests, major-element analyses, and some index parameters. It has been determined that the feldspar minerals are mechanically fractured due to weathering. The tuffs contain small amounts of clay minerals. An approximately 1-cm-thick silica-rich zone has developed under a lichen cover on the pink tuff. The chemical weathering of the tuffs produces weathered zones, which are 4.5-cm-thick within the white tuff and 2.5-cm-thick within the pink tuff. The index properties of the tuffs are slightly affected within the first 2.5 cm.

Key Words: Tuff, Weathering, Physico-chemical Properties, Midas Monument, Eskişehir, Turkey

Midas Anıtı'nın Tüfleri İçinde Gelişen Bozunma Zonunun Özellikleri

Özet: Midas anıtı, Orta Anadolu'daki Eskişehir ilinin güneyinde bulunan etkileyici bir ibadet duvarıdır. Bu anıt, tüfler (beyaz ve pembe) içinde bulunmaktadır ve anıtı oluşturan tüflerde ciddi boyutlarda bozunma problemleri vardır. Bu çalışmada, beyaz ve pembe tüflerin bozunma derinliği ve özellikleri, ince kesit, X-ışını difraksiyonu, metilen mavisi deneyi, ana element analizleri ve bazı fiziksel parametreler kullanılarak incelenmiştir. Bozunma sonucu, feldispatlarda fiziksel parçalanma tesbit edilmiştir. Tüflerde, az miktarda kil mineralleri bulunmaktadır. Pembe tüfün liken örtüsü altında 1 cm kalınlığa sahip silisli bir zon oluşmuştur. Tüflerin kimyasal bozunması sonucu, beyaz tüflerde 4.5 cm, pembe tüflerde ise 2.5 cm kalınlığında bozunma zonu gelişmiştir. Tüflerin index özellikleri ilk 2.5 cm'de az miktarda değişmektedir.

Anahtar Sözcükler: Tüf, Bozunma, Fiziko-kimyasal Özellikler, Midas Anıtı, Eskişehir, Türkiye

Introduction

The Midas monument, located in the southern part of the Eskişehir province in central Anatolia, Turkey (Figure 1), is an impressive vertical cult facade characterized by meander ornaments and pediment decorations carved into tuffs. The monument is about 17-m-wide and 20-m-high. The inscription strips on the facade are in the Phrygian alphabet. The Midas monument together with the ancient Midas city, other monuments and tombs, make this region attractive both historically and for tourism. However, previous studies (Ayday & Göktan 1990; Binal *et al.* 1997, 1998) and our field observations indicate that there is evidence of deterioration in the tuffs. Therefore, the depth and characteristics of the weathered zones developed within the tuffs should be understood for the purpose of conservation.

Site Geology

Geological studies in the region done by Özcan *et al.* (1989) and studies carried out by the present authors around the Midas monument reveal that limestone, claystone-mudstone-turbiditic sandstone, claystone-clayey sandy limestone-conglomerate, white and pink tuffs, and Quaternary deposits constitute the main lithological units exposed in the area. However, white and pink tuffs crop out widely around the Midas monument (Figure 2). The age of the tuffs is Early Miocene-Pliocene (Özcan *et al.* 1989). Within the monument, there are two different tuff units, and these units are distinguished on the basis of color and strength.

The lower part of the monument is made up of non-welded white tuff whereas the upper part of the monument is made up of slightly welded pink tuff. These

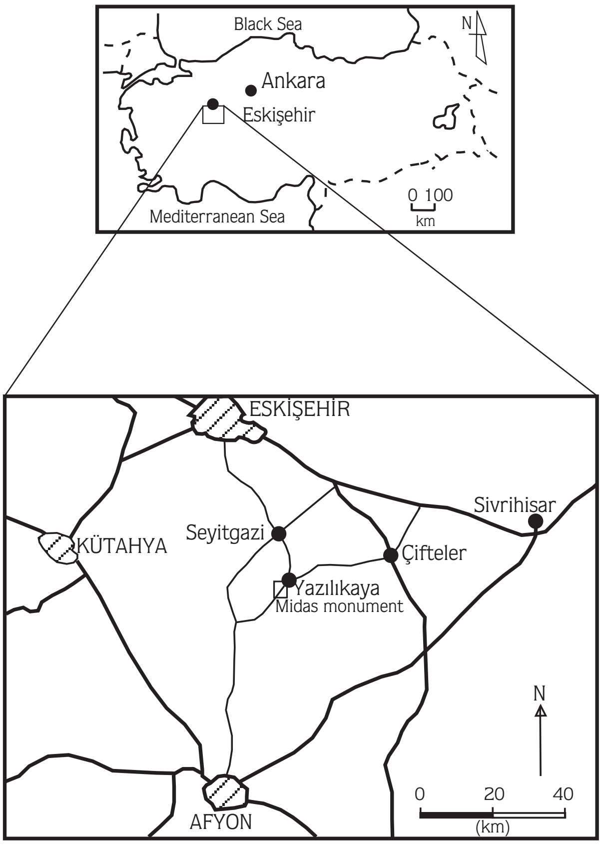

Figure 1. Location map of the Midas monument.

two units are the products of successive volcanic eruptions.

The white tuff contains phenocrysts of quartz, K-feldspar, plagioclase feldspar, biotite and opaque minerals. Various metamorphic rock fragments and pumice are also present. The phenocrysts, rock fragments and pumice are embedded in a slightly weathered tuffaceous matrix. In the tuffaceous matrix, volcanic glass shards are common.

The pink tuff has relatively higher strength than the white tuff, and contains steeply dipping columnar joints. Therefore, the pink tuff forms steep slopes in the study area. In the middle and mainly upper parts of the pink tuff, honeycomb-weathering features are present. The pink tuff contains phenocrysts of quartz, K-feldspar, plagioclase feldspar, biotite and opaque minerals. In the pink tuff, mostly pumice and rare rock fragments occur, but these fragments are larger than those in the white tuff. These fragments, along with the phenocrysts, are embedded within a tuffaceous matrix.

Physico-chemical Properties of the Weathered Tuffs

In order to determine the state and depth of weathering in the tuffs, mineralogical and petrographical, chemical, and index properties of the weathered zones of the tuffs were studied. Mineralogical and petrographical properties of the weathered tuffs were studied using a polarizing optical microscope, X-ray diffractometry (XRD) and the methylene blue adsorption (MBA) test. The chemical properties of the weathered tuffs were determined by atomic absorption. The index properties of the weathered tuffs, namely dry and saturated unit weight, effective porosity, water absorption, linear strain, sonic velocity, and point load strength index were determined. For this purpose, block samples of the white and pink tuffs were taken from the field so that samples fully incorporating the weathered zone could be studied.

Mineralogical and Petrographical Properties of the Weathered Tuffs

For the mineralogical and petrographical analyses of the weathered tuffs (white and pink), two thin sections were prepared from each tuff sample. One of the thin sections was prepared from the lichen-covered surface (0-2 cm), and the other from the fresh part of the tuffs (22-23 cm).

Thin-section studies of both white and pink tuffs indicate that some mechanical and very little chemical weathering of minerals occur near the lichen-covered surface (0-2 cm). The effects of mechanical weathering in both samples can be discerned through the degree of fracturing in feldspars. In fact, plagioclase and K-feldspars show intense fracturing; the cleavage planes are slightly widened due to mechanical weathering. There are also local indications of minor kaolinization around the cleavages in the feldspars. Biotites are slightly discolored leading to iron-oxide staining. The effects of mechanical and chemical weathering gradually decrease with depth. In the case of the pink tuff, a silica-rich zone of about 1 cm is present beneath the lichen thalli.

XRD analyses were performed on both white and pink tuff samples to assess the abundance of all minerals and the types of clay minerals within the tuffs. Two scratched samples for each tuff were selected for XRD analyses. The depths of scratches correspond to 0-0.5 cm and 14-15

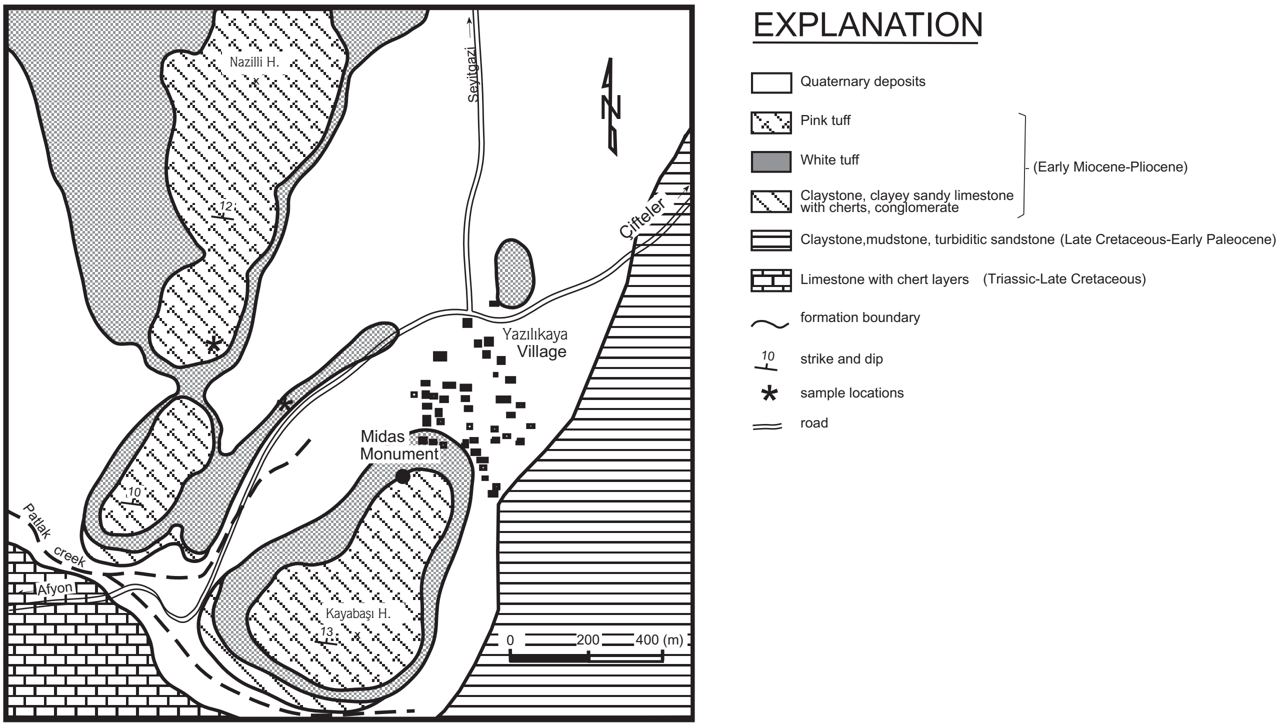

Figure 2. Geological map of the study area.

cm from the surface. The samples were then powdered to pass through a 200-mesh sieve. Two kinds of samples were prepared from each sample for analysis, namely unoriented and oriented samples. The oriented samples were tested after air-drying, glycolation, and heating at 300 ºC.

The XRD analyses of the unoriented lichen-covered white tuff reveal that K-feldspar, plagioclase feldspar, quartz, and mica (biotite) are present within the tuff. No significant peaks for clay minerals were observed, suggesting very low clay content. The oriented XRD analyses, however, indicate mainly smectite- and illite (mica)-type clay minerals. The XRD results of the unoriented lichen-covered pink tuff indicate the presence of K-feldspar, plagioclase feldspar, quartz, mica (biotite) and clay minerals. The oriented XRD analyses indicate the presence of smectite, illite (mica) and kaolinite.

The methylene blue adsorption test was performed to obtain information on the presence and properties of clay minerals in the white and pink tuffs. For each tuff, 10 samples were prepared and tested. The spot method proposed by AFNOR (1980) was used during the test. The methylene blue adsorption (MBA) values and the cation exchange capacities (CEC) of the white and pink tuffs are given in Table 1. The CEC values are plotted with respect to depth in the horizontal direction (Figure 3).

According to the test results, the CEC values of the white tuff are low (Figure 3). Near the surface (0-1 cm), the CEC of the white tuff is 4 meq/100 gr. At greater depths, it increases to 4.9 meq/100 gr - 5.0 meq/100 gr. The low CEC values of the white tuff within the first 2 cm indicate that this zone has relatively low clay content. The CEC values of the pink tuff are very low compared to the white tuff (Figure 3).

Near the lichen-covered surface (0-1 cm), the CEC of the pink tuff ranges between 1.2 meq/100 gr and 1.5 meq/100 gr, and increases to 2.1 meq/100 gr at a depth of 5 cm, and 2.4 meq/100 gr at a depth of 23 cm. The low CEC values of the pink tuff within approximately the first 1 cm indicate that this zone has relatively low clay content.

Chemical Properties of the Weathered Tuffs

Chemical weathering of rocks may cause changes in initial elemental concentrations by leaching and enrichment

Table 1. MBA and CEC of the white and pink tuffs.

Depth (cm)	White tuff MBA (gr/100 gr)	White tuff CEC (meq/100 gr)	Pink tuff MBA (gr/100 gr)	Pink tuff CEC (meq/100 gr)
0.0-0.5	1.73	4.0	0.53	1.2
0.5-1.0	1.73	4.0	0.67	1.5
1.0-1.5	1.93	4.4	0.80	1.8
1.5-2.0	2.07	4.7	0.80	1.8
2.0-2.5	2.13	4.9	0.80	1.8
2.5-3.5	2.13	4.9	0.87	2.0
3.5-5.0	2.13	4.9	0.93	2.1
8.0-9.0	2.20	5.0	1.00	2.3
14.0-15.0	2.20	5.0	1.07	2.4
22.0-23.0	2.20	5.0	1.07	2.4

(Borchardt *et al.* 1971; Borchardt & Harward 1971). In order to determine the depth of chemical weathering, major element concentrations, from the source of alteration (lichen-covered surface) at ten different depths from each block sample (a total of 20 samples), were determined by means of atomic absorption (Tables 2 & 3). Because chemical weathering is expected to be more pronounced near the source of alteration, more closely spaced samples were collected from the highly altered zones. The depths of samples from the source of alteration were 0-0.5 cm, 0.5-1 cm, 1-1.5 cm, 1.5-2 cm, 2-2.5 cm, 2.5-3.5 cm, 3.5-5 cm, 8-9 cm, 14-15 cm, and 22-23 cm.

Since the weathering products derived from the fresh tuffs are of major interest, the analytical data were normalized by dividing the elemental compositions of each sample by the same elemental composition of the corresponding fresh tuff sample. For this purpose, the white and pink tuff samples obtained from the depth of 22-23 cm were considered to be reference samples. Thus, all analyses belonging to the other depth intervals were normalized to these samples. The relative contents (normalized values) of each major element from both white and pink tuff samples were plotted against depth in Figures 4 and 5. Since the sampling points correspond to a range of depths (e.g., 8-9 cm), an average depth was used during the plotting of the graph. Considering the fact that weathering proceeds horizontally in the samples, the depth of every element analyzed is shown in the abscissa of the graph.

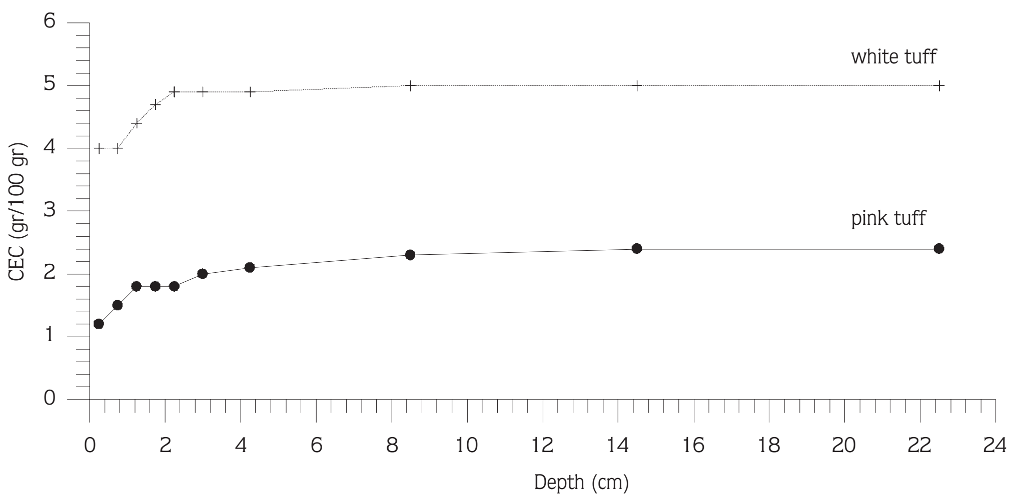

Figure 3. Variation of CEC for the white and pink tuffs.

Table 2. Major-element analyses of the white tuff.

	Depth (cm)									
Oxides (%)	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3.5	3.5-5	8-9	14-15	22-23
SiO_2	68.97	69.44	70.05	70.95	70.87	71.09	71.76	72.29	72.37	72.37
Al_2O_3	12.32	12.69	12.41	12.52	12.61	13.17	13.19	13.15	13.39	13.39
Fe_2O_3	1.02	1.03	0.97	1.01	1.05	1.04	1.03	1.06	0.97	0.97
MgO	0.13	0.15	0.14	0.13	0.13	0.12	0.11	0.09	0.09	0.09
CaO	0.96	1.18	1.18	1.12	1.19	0.98	0.89	0.84	0.83	0.83
Na_2O	1.75	1.80	1.81	1.89	1.94	1.89	1.89	1.91	1.86	1.86
K_2O	3.83	3.97	3.95	3.95	4.04	4.15	4.15	4.42	4.48	4.48
TiO_2	0.63	0.47	0.47	0.31	0.31	0.47	0.63	0.36	0.31	0.31
$H_2O^{(+)}$	9.45	8.32	8.17	7.21	6.97	6.18	5.45	4.98	4.79	4.79
SO_3	0.07	0.18	0.27	0.15	0.14	0.11	0.06	0.04	0.08	0.08
Total	99.13	99.23	99.42	99.24	99.25	99.20	99.16	99.14	99.17	99.17

Table 3. Major-element analyses of the pink tuff.

	Depth (cm)									
Oxides (%)	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3.5	3.5-5	8-9	14-15	22-23
SiO_2	73.84	75.10	73.34	72.62	72.48	71.75	72.95	72.76	72.12	72.12
Al_2O_3	12.15	12.71	13.65	14.30	14.56	14.69	14.42	14.20	14.37	14.37
Fe_2O_3	0.89	0.85	0.87	0.88	0.94	0.87	0.92	0.91	1.04	1.04
MgO	0.05	0.04	0.04	0.02	0.03	0.03	0.03	0.04	0.04	0.04
CaO	0.78	0.57	0.60	0.55	0.59	0.64	0.59	0.62	0.65	0.65
Na_2O	2.00	2.24	2.38	2.60	2.70	2.70	2.50	2.50	2.51	2.51
K_2O	3.40	3.72	4.08	4.28	4.28	4.35	4.28	4.40	4.29	4.29
TiO_2	0.31	0.47	0.47	0.47	0.47	0.63	0.47	0.47	0.63	0.63
$H_2O^{(+)}$	6.09	3.82	3.81	3.57	3.56	3.47	3.43	3.40	3.58	3.58
SO_3	0.09	0.11	0.09	0.07	0.07	0.09	0.12	0.10	0.10	0.10
Total	99.60	99.63	99.33	99.36	99.68	99.22	99.71	99.40	99.33	99.33

The relative content variations with depth for each major element in the white tuff indicate that significant enrichment of SO_3, $H_2O^{(+)}$, CaO and MgO occurs within the upper 4.5 cm of the weathered zone. However, TiO_2 fluctuates within the upper 8.5 cm (Figure 4). In the case of the pink tuff, a significant $H_2O^{(+)}$ enrichment and minor CaO and MgO enrichments within the first 1 cm of the weathering zone were observed. The general trend of enrichment ceases at a depth of 2.5 cm. On the other hand, TiO_2, K_2O, Na_2O and Al_2O_3 are slightly leached out within the first 3 cm. SO_3 values fluctuate within the upper 8.5 cm (Figure 5).

Evaluation of these analyses indicates that the depth of weathering in the white tuff is about 4.5 cm from the lichen-covered surface, whereas it is mainly confined to the upper 1 cm and slightly extends to 2.5 cm from the surface in the pink tuff.

Index Properties of the Weathered Tuffs

The effect of deterioration on the index properties of the tuffs was investigated by determining the variations of dry and saturated unit weight, effective porosity, water absorption under atmospheric pressure, linear strain, sonic velocity, and point load strength index through the

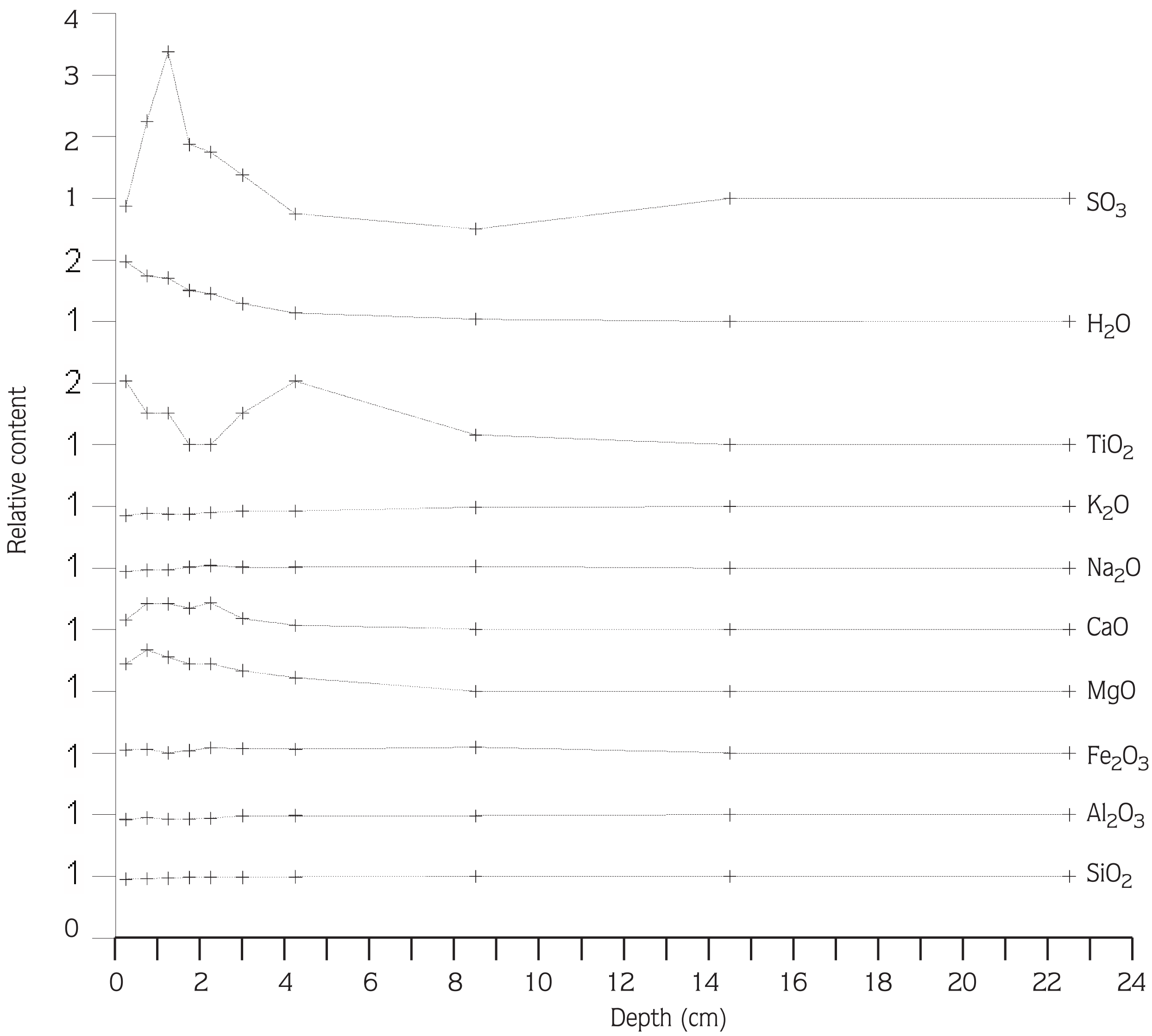

Figure 4. Relative concentration variations of the major elements in the white tuff.

weathering zones. Cube samples were prepared from five different depths in the block samples and the tests were performed on these samples in accordance with ISRM (1981), RILEM (1980), and TS699 (1987). The results are given in Tables 4 and 5, and the variations of the normalized values of the index properties of the tuffs are given in Figure 6.

Based on these tests, it was found that saturated unit weight, effective porosity, water absorption under atmospheric pressure, and the sonic velocity of the white tuff slightly increase within the upper 3.5 cm. However, no significant change in dry unit weight and point load strength index was noted through the weathering zone. On the other hand, linear strain fluctuates with abnormally high values at a depth of 17-23 cm.

In the case of the pink tuff, no significant change in dry unit weight and saturated unit weight was detected. Effective porosity, water absorption, and linear strain of the tuff slightly decrease in the 0-3.5 cm depth interval, whereas sonic velocity increases considerably in this zone. This is due to the silica-rich zone that is present within the first cm. On the other hand, the point load strength index of the pink tuff slightly increases with depth.

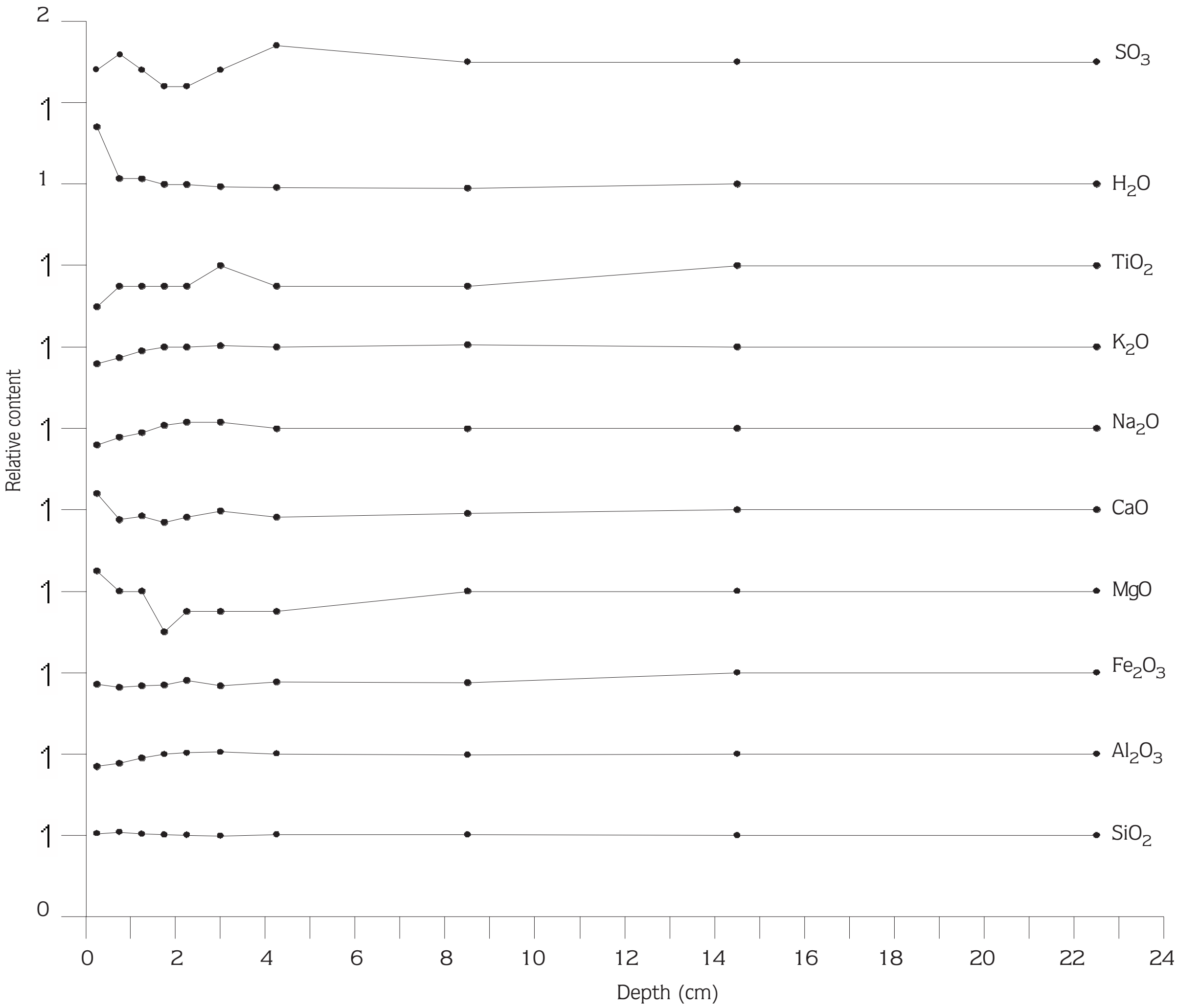

Figure 5. Relative concentration variations of the major elements in the pink tuff.

Table 4. Index properties of the white tuff.

	Depth (cm)				
	0-3.5	3.5-7	7-12	12-17	17-23
Dry unit weight, kN/m^3	11.67	11.67	11.77	11.77	11.67
Saturated unit weight, kN/m^3	16.38	16.19	16.19	16.09	15.99
Effective porosity, %	48.22	46.40	45.06	44.52	44.56
Water absorption (by weight),%	30.77	26.98	25.15	25.08	25.31
Linear strain (mm/m)	0.47	0.56	0.61	0.50	0.88
Sonic velocity-P (m/sec)	2007.52	1821.20	2047.29	2023.16	1926.87
Point load strength index, Is(50), MPa	1.19	1.20	1.20	1.22	1.16

Table 5. Index properties of the pink tuff.

	Depth (cm)				
	0-3.5	3.5-7	7-12	12-17	17-23
Dry unit weight, kN/m^3	15.21	14.62	14.91	15.01	15.21
Saturated unit weight, kN/m^3	18.44	18.15	18.25	18.25	18.44
Effective porosity, %	32.83	35.56	33.90	32.90	33.13
Water absorption (by weight),%	16.21	18.26	16.94	16.60	16.57
Linear strain (mm/m)	0.13	0.33	0.55	0.35	0.52
Sonic velocity-P (m/sec)	2661.49	1967.41	2010.01	2002.75	2033.94
Point load strength index, Is(50), MPa	1.48	1.64	1.63	1.84	1.89

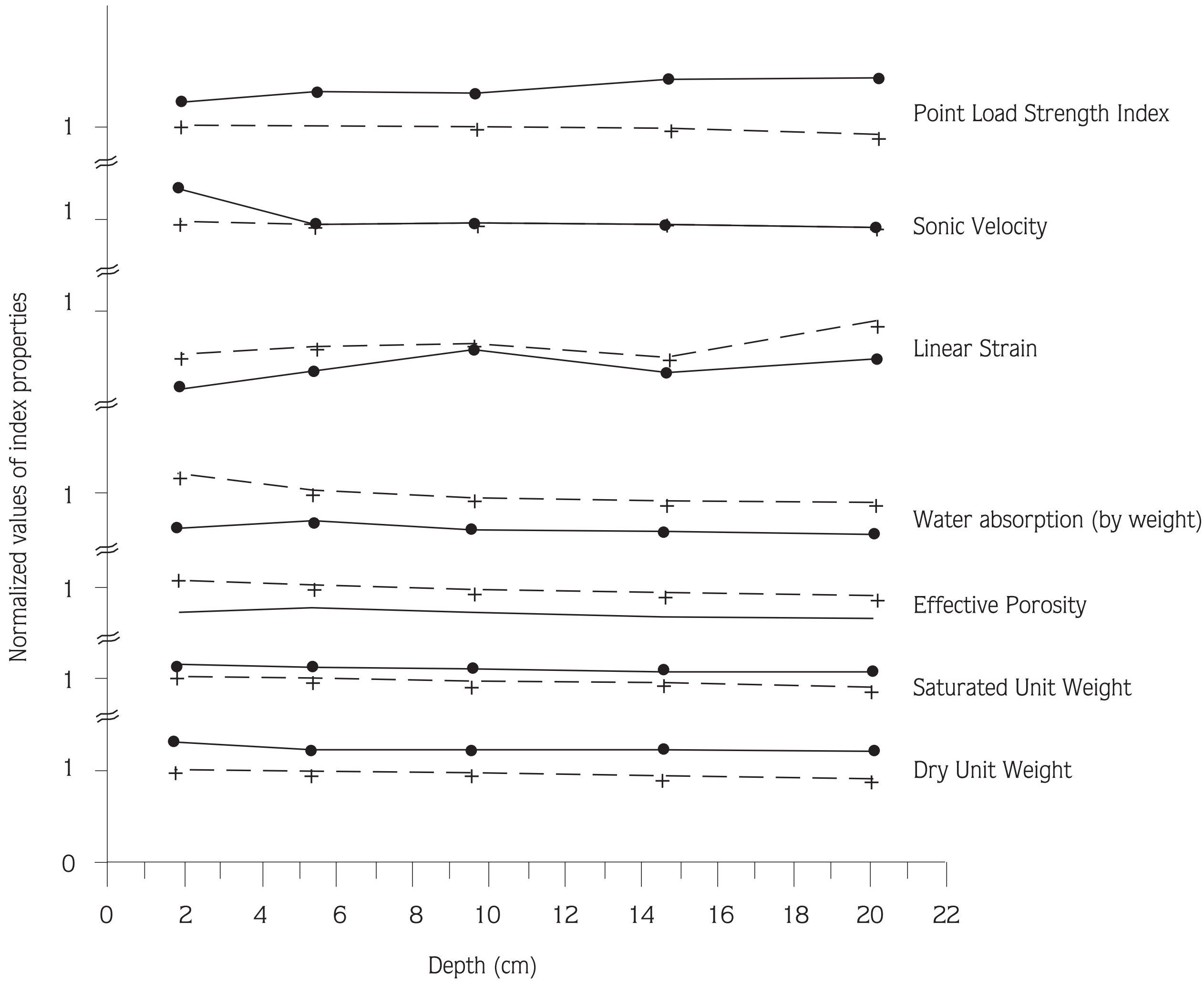

Figure 6. Variations of the index properties of the white (dashed) and pink (solid) tuffs.

The variations of the index properties with depth in both the white and pink tuffs are mainly confined to first 2.5 cm, but are not especially significant. This suggests a relatively fresh state for the tuffs. Due to the fact that linear strain is significantly affected by the heterogeneous nature of the tuffs, this parameter is not considered to be a good indicator in the assessment of weathering depths.

Conclusions

The tuffs (white and pink) of the Midas monument have deterioration problems. An overall evaluation of the mineralogical and petrographical, chemical, and index properties of the weathered zones developed within the tuffs reveals that the feldspar minerals are fractured due to mechanical weathering. Chemical weathering has produced small amounts of clay minerals, namely smectite and illite within the white tuff, and smectite, illite and kaolinite within the pink tuff. Biotites are also slightly discolored. A silica-rich zone has developed within the first cm under the lichen cover. The chemically weathered zone that has developed within the white tuff is restricted to the uppermost 4.5 cm from the surface. In the case of the pink tuff, chemical weathering has been effective within the first cm and extends laterally 2.5 cm. Due to physical weathering processes and the silica-rich zone in the pink tuff, the index properties of the tuffs are slightly affected within the first 2.5 cm. These depths should be considered in the course of conservation studies, for example, in proper consolidation treatments.

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