INTERPRETATION OF DETERIORATION MECHANISM AND CALCULATION OF WEATHERING DEPTH FOR BANGUDAE PETROGLYPHS

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Abstract

Ulsan Bangudae petroglyph (National Treasure no. 285) is the most sophisticated petroglyph among rock art discovered in Korea. It shows the life of prehistoric ancestors. In 1965, six years before the discovery of the Bangudae petroglyph, Sayeon Dam had been constructed, and the petroglyph is submerged about eight months of the year. The repeated submersion has gradually damaged the petroglyph. Hence, we have interpreted the weathering mechanism of the petroglyph surface and calculated the weathered depth using non-destructive inspection to get basic information for the long-term preservation of Bangudae petroglyph. Through the analysis, it was revealed that the Bangudae rock consists of dark-brown shale, which was changed to hornfels caused by calcite’s weathering as a result of its fast reaction with penetrated water. Furthermore, it is estimated that the weathering depth of the petroglyph is 1-4 mm from the inspection by using the transmittance property of X-rays.

Keywords: petroglyph, deterioration, weathering depth, P-XRF

1. Introduction

1.1. Background and purpose

Ulsan Bangudae petroglyph (National Treasure no. 285) is the most sophisticated petroglyph among rock art discovered in Korea. It shows the life of prehistoric ancestors. This petroglyph is considered to be the first petroglyph in Korea and the origin of Korean cultural art. In particular, the carving describing around ten types of whales and prehistoric ancestors hunting whales in a group is unprecedentedly unique, so it is enlisted in the tentative list of UNESCO World Cultural Heritage.

Bangudae petroglyph had been preserved in a good condition because of its location where it was exposed to little rainwater and because of its solid and elaborated organization of the components. In 1965, however, six years before the discovery of Bangudae petroglyph, Sayeon Dam had been constructed, and it submerged the petroglyph about eight months of the year below water. As a result, the petroglyph has been gradually damaged for about 40 years by repeated flooding (Lee and Kim 2004). Hence, to set up a long-term strategy for its preservation, studies have been conducted in various academic fields such as the humanities, natural science and engineering (Lee and Kim 2004; Choi 2002; Fitzner et al. 2004).

Despite these studies, there has been no study on the weathering process and
weathering depth of the components of the Bangudae petroglyph. Understanding of the weathering process and data on the weathering depth of each area are essential to preserve the petroglyph in the long term. This study, therefore, closely analyzes the section of the component rock to interpret the weathering mechanism of the Bangudae petroglyph's surface. In addition, the weathering depth of the petroglyph is estimated using the transmittance property of X-rays.

1.2. Method of study

A geological survey was conducted in the area near the rock to interpret the petrologic weathering mechanism of the Bangudae petroglyph and a sample of identical components with the rock components of the petroglyph was taken for quantitative analysis. Mineralogical structure and its property were observed using a Nikon Eclipse E600W polarized light microscope.

In addition, to conduct a quantitative analysis of the minerals in the rock, a PHILIPS X’pert MPD x-ray diffraction analyzer was used. The X-ray used in the analysis was CuKα and the electric power in acceleration voltage and filament were set at 40 kV and 40 mA respectively. Understanding of the chemical components of the component rock and the changes of the chemical composition by weathering was achieved by using an x-ray fluorescence analyzer (XRF) to quantify the component elements. In analyzing the contents in components of the rock surface and estimating the weathering depth, an Innov-X System P-XRF α-6000 was used.

2. Site environment

Estimated to be made in prehistoric times, the Bangudae petroglyph describing over ten kinds of whales and various creatures is carved on the rock of 15 m wide and 2.5 m high. The petroglyph is in Ulsan, located on the eastern coast of Korea. In front of the petroglyph is the Daegok stream, and the Sayeon Dam was built in 1965 to supply Ulsan city with water. The Bangudae petroglyph was discovered by an archeologist and designated as the 285th National Treasure.

The bedrock under the petroglyph is a sedimentary rock of the Cretaceous period Kyongsang supergroup, and with igneous rocks intruding the bedrock. This area consists of green-gray or dark-gray sandstone, siltstone, shale and purple siltstone, with layers of shale, sandstone. In the eastern area of the petroglyph is hornfels, distributed in a circle, which was formed from anamorphism by heated granodiorite's intrusion. Affected by the intrusion, the dark-gray shale, from which the petroglyph was carved, was also changed to hornfels, making the rock structure stronger (Hwang et al. 2010).

Average yearly precipitation from 1971 to 2010 in Ulsan area is 1,284 mm. Converted to average monthly precipitation, it was the lowest in December; 24 mm and highest in August; 234 mm. 80% of yearly precipitation is confirmed to be concentrated in the period from April to September. The Bangudae petroglyph located in an area 53-57 m above sea level is submerged below water from late spring to early winter, which makes it available only in winter and early spring.
3. Mechanism of surface weathering
3.1. Weathering characteristics

A geological survey was conducted near the site to study the traits of the component rock of the Bangudae petroglyph. According to the result, the component rock of the petroglyph is generally dark-brown and made up of sophisticated structure formed from the anamorphism. It is difficult to observe the layers on the surface of the petroglyph, which has a pattern, and the rock is mined in a massive form, which has various sizes of crevices partially near the layers.

To closely examine the surface traits of the petroglyph, samples of rock were gathered. Most of the rock distributed in the petroglyph and the same layer is a dark-brown shale (B-1) changed to hornfels. There is dark-green shale (B-2) distributed in other layers. A weathered area has been formed around 2 mm deep, which runs through the rock near microcracks. On the other hand, observing the section of the rock in the Daegok stream, which is in front of the Bangudae petroglyph, a weathered area around 10-20 mm deep has been formed in the rock (Figure 1). It indicates that weathering in the rock progresses fast under the wet condition.

![Figure 1. Weathering state of rocks around the Bangudae petroglyph](image)

A polarizing microscope was used in observing the sample rock to understand the constituent minerals, change of mineral structure by weathering, and the degree of weathering. According to the result of the observation, the Bangudae petroglyph and dark-brown shale in other areas consist of light-brown microcrystalline quartz, orthoclase, plagioclase, calcite, chlorite, mica and opaque minerals. Weathered surfaces, on the other hand, have a clear boundary with unweathered surfaces, and it is dark-gray because of the loss of minerals. Most of the component minerals on the weathered surface is quartz, orthoclase, plagioclase, chlorite, mica and opaque mineral, but calcite is not seen on the surface (Figure 2A, 2B).

A scanning electron microscope was used in observing the changes of microstructure of the rock influenced by weathering. According to the result, there are clear boundaries between weathered and unweathered surfaces, and they vary according to the degree of weathering (Figure 2C). Unweathered surfaces have a tight structure (Figure 2D) of minerals such as quartz, feldspar, calcite, etc., but weathered surfaces have many pores due to the loss of calcite (Figure 2E, 2F).

A regular pattern is observed in the rock surface regarding the size of pores. Large pores have been formed on weathered surfaces because of the loss of idiomorphic and hypidiomorphic calcite, but there is a tendency to have smaller pores and more pores on
unweathered surface. Considering the location of the petroglyph that is hardly contacted by rainwater under the prominent rock block, the rock surface with tight structure allows water to penetrate only a part of it, which leads to many pores. Through this repetitive process, it is concluded that the pores are enlarged and movement of water in the pores becomes active to enhance the micropores deep inside the rock (Figure 2C, 2D, 2E, 2F).

Figure 2. Mineralogical characteristics of host rocks around the Bangudae petroglyphs. (A, B) Microphotographs showing different color between fresh area and weathered layer. (C) SEM image showing different weathering characteristic between fresh area and weathered layer. (D) SEM image of fresh area. (E, F) SEM image of weathered layer.

3.2. Mineralogical and chemical changes

XRD quantitative analysis has been conducted to precisely analyze the change of mineral structure according to weathering. The sample of the unweathered surface analyzed in the study is from B-1 and B-2 rock, and that of weathered surface is only from BW-1, which has deep weathering. The results indicate that the unweathered surface consists of quartz (20.5%), plagioclase (28.9%), orthoclase (12.5%), mica (11.2%), chlorite (9.9%), hematite (2.2%) and calcite (15.1%). However, weathered surface consists of orthoclase (14.4%), mica (11.2%), chlorite (8.0%) and hematite (1.6%), which is similar to unweathered surface, but the content of calcite is very low (2.2%) and that of plagioclase (37.0%) and quartz (25.6%) is high (Table 1).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Albite</th>
<th>Quartz</th>
<th>Calcite</th>
<th>Orthoclase</th>
<th>Mica</th>
<th>Chlorite</th>
<th>Hematite</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-1</td>
<td>29.0</td>
<td>20.6</td>
<td>15.7</td>
<td>11.7</td>
<td>10.5</td>
<td>10.3</td>
<td>2.2</td>
<td>100.0</td>
</tr>
<tr>
<td>B-2</td>
<td>28.5</td>
<td>20.3</td>
<td>14.4</td>
<td>13.3</td>
<td>11.8</td>
<td>9.5</td>
<td>2.2</td>
<td>100.0</td>
</tr>
<tr>
<td>BW-1</td>
<td>37.0</td>
<td>25.6</td>
<td>2.2</td>
<td>14.4</td>
<td>11.2</td>
<td>8.0</td>
<td>1.6</td>
<td>100.0</td>
</tr>
</tbody>
</table>

To check the change of elements of the Bangudae petroglyph according to
weathering, the content of elements and their distribution are studied through EPMA. According to the results, K, Na and Fe are distributed evenly on both weathered and unweathered surfaces. However, Ca hardly exists on weathered surface while it is distributed evenly on unweathered surfaces (Figure 3).

Figure 3. Results of EPMA of host rock (B-1) around the Bangudae petroglyph.

In order to examine the change of components by mineralogical and chemical weathering, elemental analysis of the main components has been conducted. Analyzing the content of the main components on weathered and unweathered areas, it is revealed that SiO$_2$, Na$_2$O and K$_2$O are predominant on weathered areas while Al$_2$O$_3$, Fe$_2$O$_3$, MnO, MgO, CaO, TiO$_2$ and P$_2$O$_5$ are relatively predominant on unweathered areas (Table 2).

### Table 2. Chemical contents of host rocks around the Bangudae petroglyphs

<table>
<thead>
<tr>
<th>Element</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>Fe$_2$O$_3$</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na$_2$O</th>
<th>K$_2$O</th>
<th>TiO$_2$</th>
<th>P$_2$O$_5$</th>
<th>LOI</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-1</td>
<td>54.17</td>
<td>12.82</td>
<td>4.93</td>
<td>0.10</td>
<td>4.34</td>
<td>8.00</td>
<td>2.86</td>
<td>3.11</td>
<td>0.23</td>
<td>8.92</td>
<td>100.03</td>
<td></td>
</tr>
<tr>
<td>B-2</td>
<td>53.55</td>
<td>12.43</td>
<td>4.50</td>
<td>0.12</td>
<td>3.88</td>
<td>9.10</td>
<td>3.07</td>
<td>2.83</td>
<td>0.51</td>
<td>9.62</td>
<td>99.83</td>
<td></td>
</tr>
<tr>
<td>B-3</td>
<td>53.16</td>
<td>12.66</td>
<td>4.70</td>
<td>0.10</td>
<td>4.13</td>
<td>8.13</td>
<td>2.87</td>
<td>3.04</td>
<td>0.53</td>
<td>9.14</td>
<td>98.69</td>
<td></td>
</tr>
<tr>
<td>BW-1</td>
<td>62.24</td>
<td>14.31</td>
<td>4.97</td>
<td>0.16</td>
<td>3.81</td>
<td>0.93</td>
<td>3.58</td>
<td>3.35</td>
<td>0.61</td>
<td>4.54</td>
<td>98.75</td>
<td></td>
</tr>
</tbody>
</table>

Fe$_2$O$_3$; as total FeO, LOI; loss on ignition

In the above analysis, it is difficult to quantitatively examine the changing process of the main elements. The change has to be observed on the criteria of elemental content on unweathered areas in order to examine the change in content of the elements according to rock weathering. Generally, Al is known to hardly move during weathering (Nesbitt and Young 1982), the change of elements is examined on the criteria of this element as seen below (Lee and Kim 2004).

\[
\% \text{Change} = \left( \frac{\text{Contents of element/Contents of Al}_2\text{O}_3}_{\text{Sample}} - 1 \right) \times 100
\]

The content of CaO on weathered areas decreases 90.2% compared to on unweathered areas in the Bangudae rock. This means that the content of Ca decreases while calcite is weathered by the reaction with water. On the other hand, MnO on weathered areas increases 32.5% compared to on unweathered areas (Table 2). Mn generally is in the form of a black hydroxide that changes color of the surface of the
rock (Lee et al. 2007). In addition, according to the result that there are changes in the content of \( \text{Fe}_2\text{O}_3 \) and \( \text{Na}_2\text{O} \), calcite is not an only element that dissolves during weathering; other minerals are also weathered (Nam and Jo 1993; Kim and Jang 2006).

Considering the status of the rock weathering shown near the Bangudae petroglyph, it is concluded that the surface of the petroglyph has weathering depth to some degree. It is revealed that the weathering layer of petroglyph indicated to be formed due to quick dissolution of calcite compare to other minerals. It is also concluded that other minerals have helped slowly make pores on the surface despite their (Figure 4).

![Figure 4. Deterioration mechanism of the Bangudae petroglyph.](image)

### 4. Estimation of the weathering depth

#### 4.1. Change in chemical composition

A component analysis using P-XRF and non-destructive inspection has been conducted to examine the degree of chemical weathering of the Bangudae petroglyph. The range of it is 161 points in the petroglyph, 12 points in the unweathered rock to check the features of the distribution of the elements according to weathering. All data from the result are organized in Table 3.

According to the result of P-XRF analysis on the surface of the unweathered rock and the petroglyph, Ca and Sr have a distinguished tendency. The Ca content in the unweathered rock ranges from 60,330 to 71,369 ppm, with the average of 66,615 ppm, but the Ca content in the petroglyph ranges from 1,425 to 8,862 ppm with the average of 4,389 ppm (very low). Furthermore, the Sr content is similar to the Ca content. While the Sr content in the unweathered rock is 936 ppm on average, it is 185 ppm (relatively low) on the petroglyph surface. Sr can be replaced with Ca and a small amount of it exists in calcite.

The reason that the Ca and Sr content in the petroglyph is lower than in unweathered rock is the loss of calcite as described in the petrologic and mineralogical mechanism of weathering. In conclusion, the area where Ca and Sr content is low is the section that has more weathering.

The K content in the petroglyph surface ranges from 15,481 to 41,108 ppm with the average of 28,912 ppm, showing a normal distribution. In addition, the Ti content is 5,418 ppm on average (2,795-12,746 ppm, standard deviation 1,521), Fe content is
31,305 ppm on average (14,128-44,403 ppm, standard deviation 5,911). Mn content is 3,300 ppm on average (0-12,470 ppm, standard deviation 2,794) showing a normal distribution. The content of Zn (135 ppm on average, standard deviation 32) and Rb (116 ppm on average, standard deviation 16) also show normal distributions.

The K content in unweathered rock is 32,600 ppm on average, standard deviation 768, Ti content is 4,131 ppm on average, standard deviation 137 and Fe content is 27,685 ppm on average, standard deviation 499. The content of K, Ti and Fe in unweathered rock is included in the range of average and standard deviation on the Bangudae petroglyph surface. Therefore, it is estimated that these elements are relatively stable compared to Ca and Sr during the process of the weathering of the petroglyph. On the other hand, the Mn content in unweathered areas is below the detection limit, Zn content is detected at 65 ppm on average, standard deviation 6, Rb is 89 ppm on average, standard deviation 3. It is concluded that the content of these elements has increased during the weathering process with the eluted elements settling in the surface.

Table 3. Results of P-XRF for fresh rocks and surface of the Bangudae petroglyph.

<table>
<thead>
<tr>
<th></th>
<th>K</th>
<th>Ca</th>
<th>Ti</th>
<th>Mn</th>
<th>Fe</th>
<th>Zn</th>
<th>Rb</th>
<th>Sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>32,600</td>
<td>66,615</td>
<td>4,131</td>
<td>&lt;LOD</td>
<td>27,685</td>
<td>65</td>
<td>89</td>
<td>936</td>
</tr>
<tr>
<td>Fresh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>34,476</td>
<td>71,369</td>
<td>4,360</td>
<td>&lt;LOD</td>
<td>28,352</td>
<td>73</td>
<td>93</td>
<td>1,002</td>
</tr>
<tr>
<td>Min</td>
<td>31,550</td>
<td>60,330</td>
<td>3,938</td>
<td>&lt;LOD</td>
<td>26,501</td>
<td>52</td>
<td>85</td>
<td>872</td>
</tr>
<tr>
<td>S.D.</td>
<td>768</td>
<td>4,322</td>
<td>3,300</td>
<td>&lt;LOD</td>
<td>499</td>
<td>6</td>
<td>3</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>28,912</td>
<td>4,389</td>
<td>5,418</td>
<td>3,300</td>
<td>31,305</td>
<td>135</td>
<td>116</td>
<td>185</td>
</tr>
<tr>
<td>Bangudae</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petroglyph</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>41,108</td>
<td>8,862</td>
<td>12,746</td>
<td>12,470</td>
<td>44,403</td>
<td>228</td>
<td>150</td>
<td>932</td>
</tr>
<tr>
<td>Min</td>
<td>15,481</td>
<td>1,425</td>
<td>2,795</td>
<td>&lt;LOD</td>
<td>14,128</td>
<td>55</td>
<td>79</td>
<td>100</td>
</tr>
<tr>
<td>S.D.</td>
<td>4,707</td>
<td>1,205</td>
<td>1,521</td>
<td>2,794</td>
<td>5,911</td>
<td>32</td>
<td>16</td>
<td>113</td>
</tr>
</tbody>
</table>

<LOD; limit of detection, S.D.; standard deviation

4.2. Estimation of the weathering depth

According to the results of examination on the rock distributed near the Bangudae petroglyph, it is confirmed that weathered layers have been formed to a depth of 1-2 mm in the rock. It is, therefore, estimated that the weathering degree of the rock in the Bangudae rock is similar to this result, but it is hard to know its depth precisely. However, to preserve the Bangudae petroglyph in the long-term, the chance of desquamation has to be estimated by examining the depth of weathering in each point.

For this purpose, the weathering depth of the rock has been estimated by utilizing the transmittance property of X-rays. The transmittance degree of X-rays varies according to the density of the target object. In general, it is known that X-rays penetrate 1 mm into a rock, but 5-6 mm in soil. There is a difference between the content rates in weathered and unweathered layers. In addition, according to the results of element distribution modeling using EPMA, the Ca content in weathered layers and in unweathered layers is totally different.

Therefore, in the analysis of deep weathering using P-XRF, only weathered layers
can be analyzed since X-rays cannot penetrate into the unweathered layers. Nevertheless, in the analysis of shallow weathering, the elements that have not been detected in the weathered layers can be examined since part of unweathered layers can be examined. Weathering depth of the Bangudae petroglyph has been estimated utilizing this property.

The analysis has been conducted in weathered and unweathered layers by molding and polishing the sample with epoxy resin as shown in Figure 5. Component analysis has been conducted by grinding 0.5 mm in each area from the depth of 2.0 mm to -1.0 mm, and it was measured 5 times per each depth. The results are shown in Table 4.

![Figure 5. Verification method for calculating weathering depth using P-XRF](image)

Table 4. Variation of element contents by weathering depth of the Bangudae petroglyph.

<table>
<thead>
<tr>
<th>Depth</th>
<th>K</th>
<th>Ca</th>
<th>Ti</th>
<th>Mn</th>
<th>Fe</th>
<th>Zn</th>
<th>Rb</th>
<th>Sr</th>
<th>Zr</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>31,823</td>
<td>3,979</td>
<td>4,685</td>
<td>6,966</td>
<td>34,136</td>
<td>104</td>
<td>110</td>
<td>191</td>
<td>150</td>
</tr>
<tr>
<td>1.5</td>
<td>31,509</td>
<td>5,353</td>
<td>4,791</td>
<td>427</td>
<td>34,403</td>
<td>83</td>
<td>120</td>
<td>258</td>
<td>168</td>
</tr>
<tr>
<td>1.0</td>
<td>33,209</td>
<td>9,497</td>
<td>5,091</td>
<td>129</td>
<td>34,313</td>
<td>82</td>
<td>102</td>
<td>296</td>
<td>148</td>
</tr>
<tr>
<td>0.5</td>
<td>32,463</td>
<td>34,042</td>
<td>4,737</td>
<td>0</td>
<td>31,941</td>
<td>72</td>
<td>98</td>
<td>626</td>
<td>139</td>
</tr>
<tr>
<td>0.0</td>
<td>32,474</td>
<td>62,083</td>
<td>4,167</td>
<td>0</td>
<td>27,371</td>
<td>65</td>
<td>91</td>
<td>884</td>
<td>132</td>
</tr>
<tr>
<td>-1.0</td>
<td>32,726</td>
<td>70,547</td>
<td>4,095</td>
<td>0</td>
<td>27,999</td>
<td>64</td>
<td>88</td>
<td>987</td>
<td>121</td>
</tr>
</tbody>
</table>

The Ca content according to weathering depth increases from 2.0 mm to 1.0 mm and rapidly grows at the boundary with the unweathered layer. The change in Sr content is similar (Figure 6). This change of the content of Ca and Sr in each weathering depth has been caused by the loss of calcite, a main element in the rock, which leads to lack of Ca in weathered layers. The content of Zn, Mn, Ti, Rb, Zr and Fe, however, tends to decrease near the unweathered layer compared to the weathered layer at a depth of 2.0 mm.
Figure 6. Variation of element contents by weathering depth of the Bangudae petroglyph.

The change of element content according to weathering depth is similar to the features of the main components movement during weathering and of their distribution on the surface. It is estimated from these results that the minimal depth of X-ray penetration into the rock is over 2 mm in P-XRF.

Summarizing the petrologic and mineralogical traits and component analysis results according to weathering depth, the most relevant elements for estimating the weathering depth of the rock is Ca and Sr. On the criteria of the element content in each weathering depth, weathering depth of the rock surface can be estimated based on the data gathered in the analysis of 161 points in the Bangudae petroglyph. Considering the possible errors in the analysis caused by rough surfaces, the weathering depth has been estimated based on the change of Ca content (main component) except Sr (minor element). The weathering depth has been estimated based on the data measured in the rock by interpolation and extrapolation method in the Ca change graph.

The weathering depth at each point has been estimated by the method described above, and the distribution diagram of weathering depth has been drawn through 2D modeling. According to this result, the weathering depth of the Bangudae petroglyph surface has been estimated to be 1-2 mm. Considering the weathering depth in neighboring rocks, though the areas cannot be detected precisely, it is estimated to be 3-4 mm at the highest (Figure 7).

Figure 7. Results of calculated weathering depth of the Bangudae petroglyph.
5. Conclusions

1. The Bangudae rock mainly consists of dark-brown shale, which was changed to hornfels influenced by anamorphism. The rock has a weathering layer to some degree, and there is a difference between the mineral and chemical structures of weathered and unweathered surfaces. The weathered layer has been formed as calcite has reacted to the penetrating water and has been swept away faster than other minerals.

2. The content of Ca and Sr in the Bangudae petroglyph is estimated to be much lower than in the unweathered rock. According to the result in an analysis on the weathering depth of the petroglyph by utilizing the transmittance property of X-rays generated from P-XRF, the weathering depth in the surface of main rocks has been detected to be 1-2 mm. Furthermore, considering the weathering depth of neighboring rocks, it is estimated to be 3-4 mm at the maximum in the areas where the depth is estimated to be over 2 mm.

References


