Conservation of a decorated ancient tomb in harsh climate conditions

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Contents

Chapter 1. General Introduction

1.1 Research background

Preserving and maintaining the paintings, drawings or line engravings on the wall of decorated ancient tombs[1] in their original form is important. Such decorations were created only on the wall and ceiling surface or stone surface. Based on their intent and significance, the murals can be divided into several types in terms of their usage and dedication, such as mural paintings in buildings of the city and within churches or temples, mural painting in grottos or caves, and mural painting in tumulus or underground tombs related to funeral rituals. Examples of mural paintings are preserved in ancient temples, and include UNESCO World Heritage Sites such as the Archaeological Areas of Pompei and Herculaneum and Torre Annunziata in the Naples province, Italy (UNESCO, 1998; Sheldon, 2013), the Horyu-ji Temple in the Nara prefecture, Japan (UNESCO, 1993), the Yungang Grottoes in Shanxi province (UNESCO, 2001), the Mogao Caves south-east of the Dunhuang oasis in Gansu Province, China; and the first Buddhist caves, namely the Ajanta Caves, in Maharashtra State, India. The Ajanta caves are decorated with fascinating wall paintings executed between the 2nd century BC and the 6th century AD (Gontareva et al., 2015).

Steppe nomads have been herding livestock for many centuries, moving around and depending on pasture resources, thus, creating a way of life called the nomadic culture in world history. However, nomads did not simply move around during their thousands of years of reign in the central Asian plateau. They have built military settlements and constructions that can be seen as monuments of the Mongolian cultural heritage. There are only a few mural paintings in Mongolia, one of sample is the mural paintings of Erdene Zuu, the earliest surviving Mongol Buddhist monastery (UNESCO, 2004; Onoda, 2012). Since 2000, the number of archeological excavations in Mongolia has increased sharply. As a result, fragments of mural paintings have been found in the ruins of Kharbalgas, the 8th century capital of the Uighur dynasty (Hüttel & Erdenebat, 2009; Erdenebat et al., 2010) and in the ruins of Kharakhorum, the 13th and 14th century capital of Chingis Khan's vast Empire (Erdenebat, 2020) as well as Ikh Bulagiin Öndör Dovjoo ruin (Tsogtbaatar et al., 2019; Angaragsuren & Kohdzuma, 2020). A fragment of a mural was also found in a tomb at the Khundiin Khooloi site (Ochir et al., 2010). In 2011, a decorated ancient tomb with mural paintings, named Shoroon Bumbagar, was discovered for the first time in Mongolia (Yatsenko, 2014). The tomb was constructed in the second half of the 7th century. It is evident that the tomb was built according to the burial rites of the Tang Dynasty. Dozens of artifacts have been found in it (Solongo et al., 2016; Yilmaz, 2020; Narantsatsral, 2018). In a research fiction named "Turkish Ulaan Kherm Mural tomb of Mongolian plateau" by Ushio (2013), author noted that the buried person was a high ranking person according to the Tang dynasty policy. In addition, a variety of rare and precious textiles were found in the tomb, which is another key indicator of the status of the person in the tomb (Murakami et al., 2021).

[1] The Japanese Archaeological Dictionary defines the term "decorated ancient tomb" as a general term for an ancient tomb with decorations, such as color patterns, mural paintings, reliefs, or line engravings on the wall's surface (Tanaka & Shinhen, 2002)

Underground tombs from the Tang Dynasty are commonly found in Xi’an in Shaanxi province, China (JCICC & NRICP, 2006). The fact that this type of tomb was found on the Mongolian plateau is an important contribution to historical and cultural heritage and reflects the relationship between the Turkic Dynasty and the Tang Dynasty.

Owing to the use, importance, and risks of mural paintings, there are two general approaches to preservation. There is a trend that advocates the preservation of the original mural paintings at the original site. For example, decorated ancient tombs in Japan are protected in situ (Figure 1.1). However, in the case of a significant threat to the preservation of the tomb, an intervention may be undertaken to remove the mural painting from the original site and to preserve or study it in a museum environment. As threats are common in China, mural paintings are removed from walls and placed in storage. In Japan, the Takamatsuzuka tumulus (Special Historic Site) was protected in situ from 1972 to 2004 (Figure 1.2). Unfortunately, the murals were removed from the mound together with the stone chamber to keep in a suitable facility, as it became clear that mold was growing on the surface of the mural painting. The dismantling of the chamber has already been undertaken. In the future, their return to the original site will only be possible once facilities are erected that would be impervious to future effects of environmental damage such as mold.

Figure. 1.1. Garandoya tumulus, Oita prefecture, Japan

Figure. 1.2. Takamatsuzuka tomb, Nara prefecture, Japan. “Asuka Bijin” (Asuka Beauties), an ancient mural depicting beautiful women at the Takamatsuzuka tomb (left), and burial mound (right)

Since the discovery of underground tomb with full mural paintings in Mongolia, the policy of the Ministry of Education, Science and Culture of Mongolia was to preserve them at the site and present the site to the public, and placement in a long-term museum is planned (Lunsford, 2012). After the completion of the excavation of the Shoroon Bumbagar tomb in Mongolia, the mural paintings were still in a good condition. At the time, the Mongolian team carried out protection works for the preservation of the mural paintings in situ. For example, to protect the murals from the effects of natural precipitation, permanent shelter with metal panels was constructed above the tomb (Figure 1.3.a). In addition, a consolidation solution was applied on the mural's surface (Figure 1.3. c). The emergency team also installed wooden propping, and supports inside the tomb to protect the airshaft, antechambers and burial chamber from collapse (Figure 1.3.d.e). From 2012 to until now, conservators of National Centre of Cultural Heritage of Mongolia (NCCH) have worked onsite and carried out removal of fungi and microorganisms on mural paintings. Also, the National Center for Cultural Heritage closes the open dromos and airshafts of the Shoroon Bumbagar tomb in November and reopens these between May and June.

Figure 1.3. Mongolian team carried out protection works for the preservation of the mural paintings in situ. a) Permanent shelter with metal panels, b) Open dromos condition (closure method), c) Consolidation intervention, d), e) Work to prevent the mural painting from collapsing

In addition to Mongolian team working on the preservation of the mural paintings, international experts were invited to conduct research recommendations. Here is a brief chronological order:

In 2012, the Mongolian authorities requested that an international expert travel to Mongolia to preserve the Shoroon Bumbagar tomb. The aim of the project was to provide technical assistance for the conservation of mural paintings, the provision of guidelines for mural painting conservation-restoration, and training needs assessment for capacity building in the short term. The long-term objectives foresee the provision of assistance for the visitor's management plan and for the construction of an underground museum at the tomb's site, depending on the feasibility of the execution of such a project (Lunsford, 2012).

In 2013, researchers of Japanese company Saishiki Sekkei worked on site and carried out surveys to make copies of the mural paintings. Hiroshi Yamaguchi (Tezukayama University) also carried out 3D documentation inside the tomb.

In 2013, the next UNESCO expert visited Mongolia, and fieldwork was carried out on site. The activities included assessing the current status of the conservation of the tomb, providing practical training to Mongolian national experts pertaining to the conservation and preservation of tombs, including the consolidation and stabilization of the site according to international standards, and assisting Mongolian national experts in carrying out immediate actions to ensure the protection and preservation of the site as well as providing guidance to Mongolian national experts regarding immediate follow-up actions and long-term actions to be undertaken to ensure the appropriate preservation and conservation of the site (Margottini, 2013).

From 2014 to 2019, UNESCO experts carried out on site field surveys under the framework of protecting, conserving, promoting, and transmitting tangible heritage of the UNESCO/Monaco Fund-in-Trust project "Capacity-Building and Awareness-Raising for the Preservation, Conservation, Visibility, and Sustainable Management of the Archaeological Site of Shoroon Bumbagar of Mount Makhan, Mongolia" in addition to holding a series of capacity-building workshops for the preservation and conservation of ancient mural paintings at the site (Lunsford, 2015, para.1). Within the framework of cooperation, re-positioning of paint layer detachment, desalination test and removal of micro-organism from the wooden propping were carried out (Figure 1.4). Moreover, a Turkish Cooperation and Coordination Agency (TIKA) specialist visited the site and carried out a field survey and some preservation activities that digging the trench at the north side of the tomb and installing drainage pipes and pump for extracting water concluded (Figure 1.5).

Figure 1.4. Preservation-Conservation workshop (UNESCO). a) Re-positioning of paint layer detachment, b) Desalination test, c) Removal of microorganisms from wooden propping

Figure 1.5. The trench was dug about 50-60 m north of the tomb's fence

However, after the above all activities such as protection work, consulting service for preservation, documentation works and preservation-conservation workshop were carried out, the mural paintings continued to deteriorate daily (Figure 1.6). How to protect the murals in site in dry and harsh climates is one of the most pressing issues in the field of mural painting preservation.

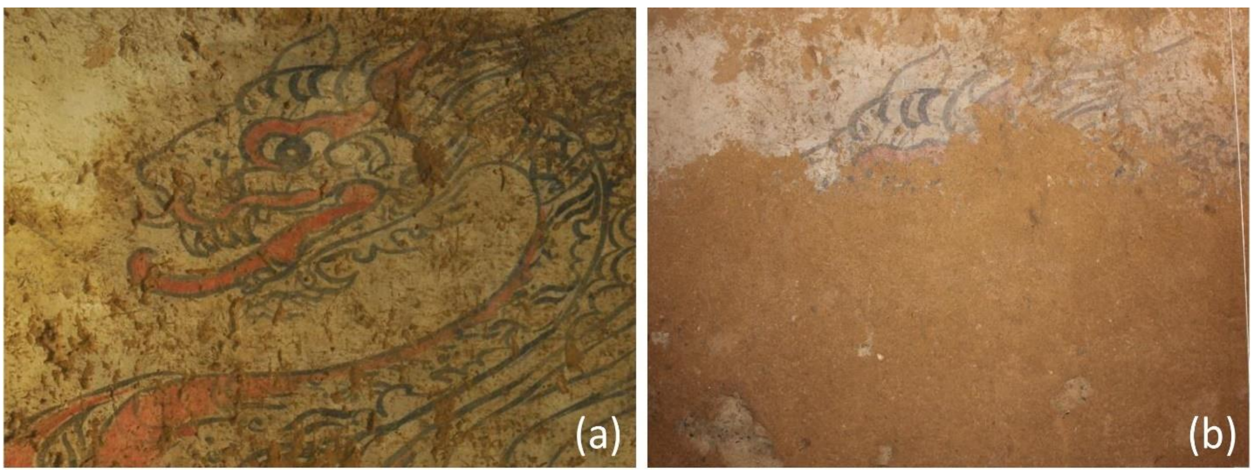

Figure 1.6. a) Mural condition after finished excavation (September 2011), b) Mural condition in September 2017

1.1.1 General issues in the preservation of the mural paintings

There are many factors that can damage a mural painting in cultural heritage field. These factors can generally be divided into several categories, including biological weathering, chemical weathering, and physical weathering.

Deterioration of wall paintings caused by biological weathering is a serious problem in the field of cultural heritage (Figure 1.7). Biological weathering can be attributed to the increasing level of biodeterioration observed in decorated tombs and mural paintings (Kiyuna et al., 2021; Kiyuna et al., 2018; Kigawa et al., 2013; Wang et al., 2010; Miura, 2007). Microorganisms like fungi, algae, and lichens develop rapidly when exposed to air with a relative humidity of over 65%. They may take the form of stains or they may be spotty in character and of varied color, and change the appearance of the paint layers and the rendering of the decorations (Mora: 1974).

Chemical weathering is mainly due to dissolution, hydrolysis, action of carbonic acid, hydration, and oxidation. Damage can cause the pigment used in the mural paintings to change (Figure 1.8.a). For example, copper and chlorine show a progressive inward transformation of the blue azurite particles to the green pigment atacamite (Schilling et al., 2004, p.443). Orpiment pigment loses its color to form white arsenic trioxide. Realgar pigment is transformed into pararealgar, orpiment, or arsenic trioxide after exposure to light (FitzHugh: 1997). Some studies have shown the discoloration of red lead pigment (Qingping et al., 1999; Aze et al., 2007).

Figure 1.7. Biological weathering on the Takamatsuzuka mural painting. "Asuka Bijin" mural is shown as it was first discovered in 1972 (left), darkened by mold in 2006 (center), and current condition (right). (© The Japan times).

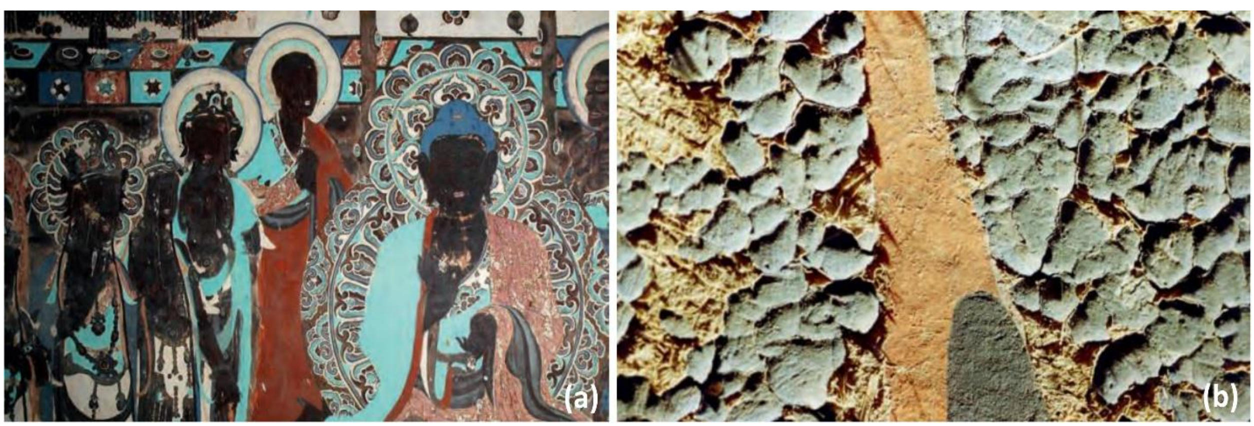

Figure 1.8. Deterioration of the mural painting. a) Chemical weathering: pigment discoloration, fading of the mural painting. b) Physical weathering: detachment, flaking and surface peeling of the Mogao Grottoes, China (© Li Zuixiong)

Physical weathering is caused by expansion and contraction due to changes in temperature, moisture absorption and desorption, and crystal growth in ice and salt (Figure 1.8.b). Numerous studies have shown that damage to any material can result from repeated drying and wetting cycles. Also, the most extensive damage in the field of cultural heritage can occur due to repeated freezing and thawing cycles. Freezing water in stabilized materials produces expansive forces that cause the formation of micro cracks, an increase in volume, and bond breakage (Makusa:2015).

The presence of salt is one of the main causes of weathering in mural paintings and stone statues. Salt crystallization may be locally concentrated as efflorescence on the surface of the mural or less apparently as subflorescence in the undersurface of the mural paintings that also causes mechanical damage (Schwarz et al., 2008, Arnold et al., 2013; Zehnder, 2007).

1.1.2 The problems of a decorated ancient tomb in harsh climate conditions based on the Shoroon Bumbagar tomb

In cold regional climates, repeated freezing and thawing cycles can have a detrimental effect on mechanical properties of soil and sediments. In addition, ventilation changes the normal ambient temperature and humidity and can cause any material to lose moisture or dry out. In particular, in the case of underground tombs with open entrances, the ingress of cold, dry and humid air directly affects the preservation conditions of the murals and causes damage due to rapid moisture loss or condensation.

The Mongolian climate is characterized by long cold winters, dry and hot summers, low precipitation, and large temperature fluctuations. Across the country, meteorological records show an extreme minimum temperature of -52.9 °C in January and an extreme maximum temperature of 43.1 °C in July (Batima and Dagvadorj, 2000). As for the preservation condition of mural paintings in such harsh and extreme climates, detachment and peeling of the paint layer were observed in some areas of the mural painting of the open dromos and airshafts. In addition, the wooden props that act as supports were nearly entirely covered by microorganisms (Lunsford, 2012). It was assumed that the shelter was built over the tomb to protect it from direct natural factors such as sun rays, wind, and precipitation. However, the mural paintings have been deteriorated over time. Thus, examining what type of damage occurs in which part of the tomb is crucial. It is necessary to determine how this deterioration affects the mural paintings as well as to determine the cause of the damage. The environment survey inside the tomb and the shelter not only contributes to the study of the preservation of the tomb but is also highly effective in the study of the preservation of underground tombs in extremely cold regions.

To establish a preservation methodology for mural paintings in underground tombs in Mongolia, first, the materials, conditions, and causes of deterioration of the mural paintings should be investigated. Control of the environmental factors and restoration method should then be discussed based on the above-mentioned information.

1.2 Aim and Objectives

This study aimed to examine the influence of the surrounding environment on the microclimate within the Shoroon Bumbagar tomb. Moreover, the internal environmental changes due to the external environment were assessed by keeping open dromos closed during the cold season and open during the warm season. In addition, control of the environment to suppress salt precipitation around the mural paintings of the open dromos is discussed. Therefore, the materials used for the mural paintings in the Shoroon Bumbagar tomb were investigated first. In addition, the physical and biological deterioration that occurs within the tomb was observed, and an environment survey was carried out within the open dromos, the airshafts, the burial chamber, and the shelter as well as outside the shelter.

In this case study, a hydrothermal environment survey of the Hasugaike Yokoana tombs No.16 and No.17 in Miyazaki, Japan, was conducted to help understand the relationship between the environment outside the shelter and the microclimate inside the Shoroon Bumbagar tomb. In this study, results of the influence of the surrounding environment on the microclimate of both tombs and determination of the wetting and drying cycles in the tomb due to seasonal changes as well as a method for suppressing the impact of the deterioration were included.

This thesis consists of the following chapters (Figure 1.9):

Chapter 1 summarizes research background and purpose.

Chapter 2 provides a brief overview of the excavation, structure, and mural paintings of the Shoroon Bumbagar tomb, and the climate of Mongolia and the site and conservation activities are summarized in chronological order. In this chapter, the geological setting of the site is discussed.

Chapter 3 focuses on the investigations of painting materials used for the mural paintings of ancient underground tombs. This chapter is currently under review for publication, and it was published in the "Journal of Conservation Science" of the Independent Administrative Institution Tokyo National Research Institute for Cultural Properties.

Chapter 4 presents an observational survey of the deterioration in the burial chamber, airshafts and open dromos. In this chapter, the deterioration factors affecting mural paintings are explained.

Chapter 5 discuss a study on the preservation of the Shoroon Bumbagar tomb based on an environmental survey. In this chapter, observation survey results, deterioration factors affecting mural painting, a survey of the thermal environment inside the tomb, and examination of the thermal environmental survey results after closed and open intervention are discussed. This chapter was published in "Studia Archaeologica".

Chapter 6 presents a case study of a hydrothermal environmental survey of the Hasugaike Yokoana tombs. In this chapter, the results of the environmental conditions inside the tombs during the four seasons, the impact of the microclimate, methods of suppressing the deterioration of the tombs, and examination of the preservation condition after closure of tomb No.16 are discussed. This chapter is currently under review for publication, and it was published in "Cultural Heritage Study".

Chapter 7 summarizes the research undertaken, reviews the conclusions reached, and offers recommendations for future work to be undertaken.

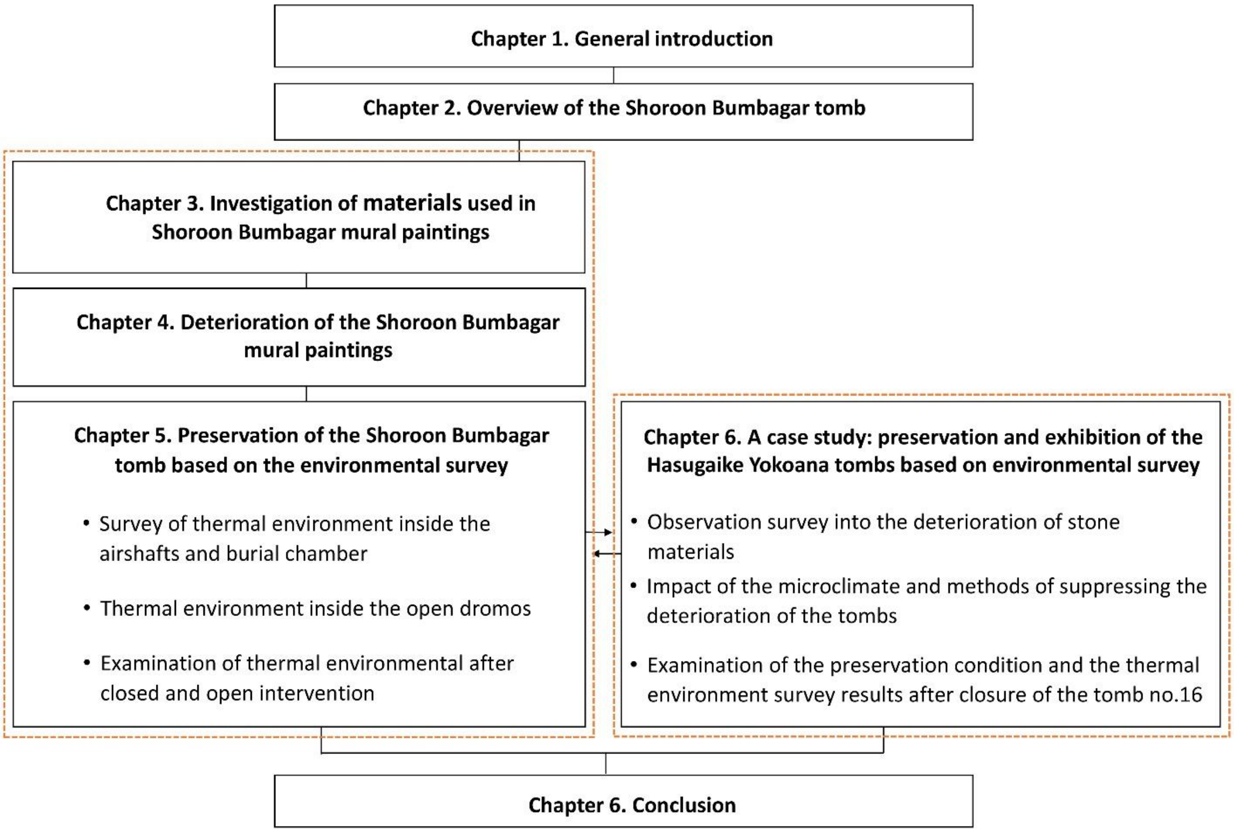

Figure 1.9. Thesis consist (structure)

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Chapter 2. Overview of the Shoroon Bumbagar tomb

2.1 Introduction

In Chapter 2, the history of excavation, structure, and mural paintings of the Shoroon Bumbagar tomb are introduced. The murals of the tomb have been conserved in-situ since their discovery; however, these were unfortunately lost by powdering. To discuss the possibility and methods for the in-situ conservation of murals, it is important to understand the deterioration phenomena of the murals and its causes. In this chapter, the geological setting and climatic conditions of the Shoroon Bumbagar tomb as well as the in-situ conservation activities are described.

2.2 Overview of the ruin

The Shoroon Bumbagar tomb[2] is located in the valley of the Tuul river, toward the northern side of the Ulaan Kherem ruins and the south slope of the Maikhan Mountain, 14 km northeast of the Bayannuur village of Bulgan province or 210 km to northwest of Ulaanbaatar, the modern capital of Mongolia (Figure 2.1a). The tomb was discovered in 2001 and an excavation operation was carried out by a joint team of archaeologists from the Institute of History of the Mongolian Academy of Sciences and the Eurasian University of Kazakhstan in July–August 2011 (Lunsford, 2012, p.5). This tomb was designated as a national historic site of Mongolia in 2020.

According to a recent study, additional five tombs of similar design were detected in this region. Some studies have suggested the following hypotheses regarding the date of creation of the Shoroon Bumbagar tomb. In 2009, Shoroon Dov of Zaamar,[3] which is situated approximately 11 km east to the opposite riverside of the Tuul river near the Shoroon Bumbagar tomb, was discovered by a joint archaeological team of Mongolia and Russia. Two inscriptions in Chinese were found carved on limestone, which were the primary sources for the review of the historical information. The epitaph revealed that the tomb was the final resting place of Pugu Yitu 僕固乙突 (635-678), who was the leader of the Pugu tribe that belonged to the Tiele Confederation (Skaff, 2019). The tomb was similar to the Shoroon Bumbagar tomb of Bayannuur, with similar artifacts found in the tomb. It was possible that these two tombs could be related to each other. Thereof, Batbold (2017) assumed that the tombs were built for the deceased, who were the high ranking persons of the tribe. In addition, based on the research titled, "The Pu-gu, a forgotten tribe," it was speculated that the Shoroon Bumbagar tomb was likely built in 657 AD. Furthermore, he submitted

[2] The tomb has been known by several names since its discovery. Local people refer to the tomb as "Shoroon Bumbagar (round earthen mound). Some researchers have adopted a different nomenclature, referring to it as "Shoroon Bumbagar on Mount Maikhan" (Chuluunbaatar, 2016), "Shoroon Bumbagar tomb" (Narantsatsralt, 2018), (Yatsenko, 2014) or "Bayanuur tomb" (Skaff, 2019). In this study, it has been referred to as the "Shoroon Bumbagar tomb."

[3] Some researcher called it "Shoroon Bumbagar of the Zaamar" and "Pugu Yitu tomb" (Skaff, 2019). G.Batbold, (2017) referred to it as "Shoroon Dov mausoleum".

a proposal that there may be a tomb for the son (Sifu 思匐) of Pofu Qilifa Gelan Boyan 歌滥拔延, the leader of the Pugu tribe (Batbold, 2017).

From the tomb, 550[4] archaeological objects were found, which were primarily made of gold, silver, bronze, copper, glass, textile, wood, terracotta, bone, gilded bronze, and fragments of paint that on silk as well as mural paintings. Most of these findings were similar to those of the Tang dynasty. The discovery of Byzantine and Sogdian coins suggested that the tomb dated back to the middle of the seventh century.

2.2.1 Tomb structure

The Shoroon Bumbagar tomb is composed of a burial chamber, four rectangular airshafts, and an open dromos. The open dromos is located downward to the entrance of the first airshaft with a slope. The four airshafts are connected through tunnels. The fourth airshaft has a niche on both sides and is connected to a short tunnel that connects the subterranean burial chamber (Figure 2.1b). The horizontal length from the entrance of the open dromos to the back wall of the burial chamber is approximately 42 m; the open dromos is approximately 17 m in horizontal length and 120–130 cm wide; each niche measures 100 (W) × 100 (D) × 100 (H) cm3 and has a wooden door; each airshaft measures approximately 200 (W) × 200 (D) cm2; each tunnel has 150 (H) × 140 (W) cm2, and the burial chamber adjacent to the short tunnel measures 370 × 350 cm2. The tomb entrance is the ground level, and the slope downward to the first airshaft is at a depth of approximately five meters below the surface. The mound on the ground surface is 4.2 m high and has a diameter of 36 m. It is built with superimposing layers of clay soil using the tamped earth method (Ochir et al., 2013).

2.2.2 Mural paintings

The walls of the open dromos, airshafts, and burial chamber contain mural paintings. An image of a white tiger on the western wall of the open dromos is the largest among the mural paintings of this tomb, with a length of 7.8 m; this image is the largest among the mural paintings of the tombs discovered till date in Asia. In addition, paintings including 24 portraits of people painted in red, brown, light gray, and dark gray colors, two saddled horses with two grooms, two Buddhist temples, a jeweled lotus flower, monster mask, flags, and seven trees (Narantsatsralt, 2018) have been found. The locations of the wall paintings are grouped as follows (Figure 2.1b).

- West and east side of the open dromos
- Upper part of the north wall of the open dromos
- West and east sides of the first open airshaft
- Upper part of the north wall of the first airshaft
- West and east sides of the second open airshaft
- Upper part of the north wall of the second airshaft
- Upper part of the north wall of the fourth open airshaft

[4] There is difference in the numbers of artifacts found from the tombs in some studies. In particular, in a research fiction named “Rare Archaeological Musical Artefacts from Ancient Tomb in Mongolia” by the author, Chuluunbaatar (2016), it was noted that 509 archeological artifacts were found.

- Corner walls of the fourth airshaft
- Walls inside the burial chamber

Figure 2.1. a) Location of the tomb, b) Structure of the underground tomb

Sergey A. Yatsenko clearly included the image of the mural painting in his research. On the west and east sides of the open dromos were the tiger and dragon, and on either side of the northern end of these walls, groups of three men dressed in red and brown caftan that pledged to each other with a sword were standing under three banners (Figure 2.2). The north wall of the open dromos above the entrance to the corridor with covered passages and airshaft was depicted as a wooden building with roof eaves from which the birds could fly away (Figure 2.4a). On the walls of the first airshaft (on either side) were included two grooms dressed in a Turkic costume holding the two saddled horses (Figure 2.3). The upper part of the north wall of the first airshaft had a lotus flower (Figure 2.4b) (Yatsenko, 2014).

In the next compartment, that is the second airshaft, family members of the deceased were shown on both sides. The portraits of a man and lady were included on the west and east walls. On the west side, a man dressed in a Turkic caftan and a lady dressed in the Chinese costume of that period were shown (Figure 2.5a). Unfortunately, the left portraits were poorly preserved. The image of the youth and young lady with the Chinese costume was included on the east wall (Figure 2.5b, c). On the upper part of the north wall of the second airshaft, a mythical animal head [5] was displayed (Figure 2.4c). The image on the east wall of the third airshaft contained a standing man and a dog (Figure 2.5d). The men dressed in black and red caftan with hats were observed on the south and north sides of the antechamber located on the east and west walls (Figure 2.6). On the upper part of the north wall, a wooden building was observed (Figure 2.4d).

In the burial chamber, the mourners including the junior members and young relatives who were praying for the deceased were shown. The left of the entrance showed a symbolic row of men and women (seven of them preserved) with a predominant red colored attire. Each of them prayed next to a tree (Figure 2.7).

[5] Some references were described as "Head of an animal alike a cow" (Lunsford, 2012, p.7) and "Monster face" (Narantsatsralt, 2018, p.240).

Figure 2.2. Mural painting on the east side of the open dromos (© Institute of History and Archaeology)

Figure 2.3. Mural paintings on the west side of the first airshaft (left) and (right), (© Institute of History and Archaeology)

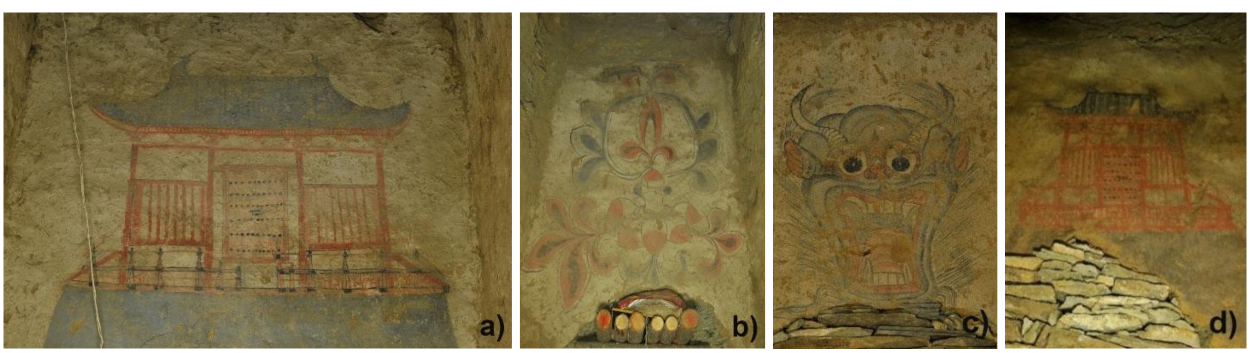

Figure 2.4. a) Mural painting on the north wall of the open dromos, b) ‘Lotus flower’ painting on the north wall of the first airshaft, c) ‘Myth animal head’ painting on the north wall of the second airshaft, d) ‘wooden building from which its roof eaves’ painting on the north wall of the fourth airshaft

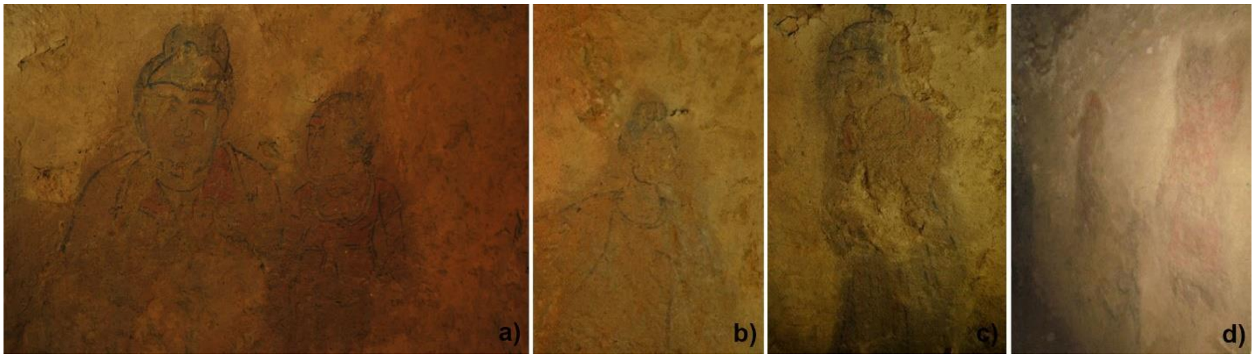

Figure 2.5. a) ‘A man and lady’ painting on the west wall of the second airshaft, b, c) ‘Youth and young lady’ painting on the east wall of the second airshaft, d) ‘Two men’ painting on the east wall of the third airshaft

Figure 2.6. ‘A standing man’ painting which is painted on the south and north side of the niche

Figure 2.7. The mural painting inside the burial chamber (© Institute of History and Archaeology)

2.3 Geological setting

One of the features of the site is its natural saline formation are widely distributed. There are small salt lakes to the west of the Shoroon Bumbagar site (Figure 2.8).

Figure 2.8. Salt lake near the Shoroon Bumbagar site

The geological setting of the Shoroon Bumbagar site has been clarified by several surveys. Margottini described that the tomb was located in an area characterized by basin deposits, mainly continental clastic sediments covering a metamorphic rock, mostly comprising phyllite and schist. The tomb is excavated in the metamorphic rock formation, mainly comprising is mostly phyllite and schist and is highly foliated with interbedded clay. The top part is composed of continental clastic sediments, mainly sand and silt (Margottini, 2013, p.5). In addition, in his report “Second workshop on the stabilization of archaeological tombs at the site of Shoroon Bumbagar of Mount Maikhan and preservation-conservation of ancient mural painting,” Guerra described the geological setting of the Shoroon Bumbagar site as “…the section includes at the top 0.8–1 m thick, white fine sands; below up to the bottom of the trench, a coarse clastic deposit representing the slope debris mainly derived by the rock basement of fractured schists” (Guerra, 2016, p.6).

Additionally, Bolormaa carried out a geological setting survey at the Shoroon Bumbagar site and determined that the Khara formation with sandstone–alluvial–schist bed was spread at the location of the site. The site is covered by evenly spread Modern Quaternary (p-QIV) dark fertile soil, containing plant roots and humus at a depth 0–0.5 m (Figure 2.9, Soil profile: A horizon). Underneath the Upper and Modern Quaternary (dp-$Q_{III\text{-}IV}$) light grey coarse-grained soil of fluvial origin, clayey sand basement soil is spread at a depth 0.5–1.5 m (Figure 2.9, Soil profile: B horizon). The burial chamber of the Shoroon Bumbagar tomb is located across, the Upper and Modern Quaternary (ed-$Q_{III\text{-}IV}$), with light greenish blue and gray coarse-grained soil of fluvial origin, silt, and clayey sand with gravel basement soil level, and deep in the erosion zone of the weathered alluvial schist (Figure 2.9, Soil profile: C horizon), (Bolormaa, 2016).

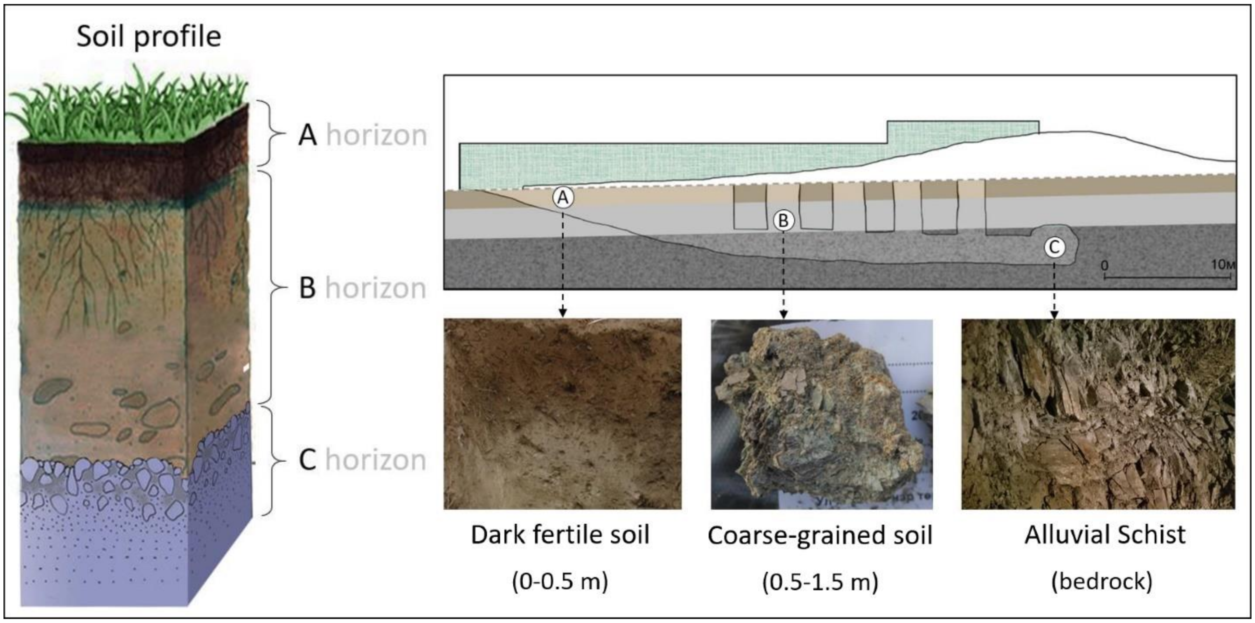

Figure 2.9. Soil profile of the site

2.4 Climate of Mongolia and Shoroon Bumbagar site

Mongolia has a harsh continental climate with long, dry and extremely cold winters, hot summers, and low rainfall. Furthermore, the annual and diurnal temperature variations are large, and the number of sunny days per year is relatively high, that is an average of 260 days. Mongolia's climate is colder than that of other countries in the same latitude. The average annual air temperature in Mongolia is 0.7 ºC; it is +8.5 ºC in the warmest regions of the Gobi and southern Altai deserts, and -7.8 ºC in the coldest region of the Darkhad depression (northern Mongolia).

January is the coldest month with an average temperature of -15 ºC to -35 ºC. Breaking down by the region, it is -30 to -34 ºC in the valleys of the Altai, Khangai, Khuvsgul, and Khentii mountains, -25 ºC to -30 ºC in the high mountainous area, -20 to -25 ºC in the steppe, and -15 to -20 ºC in the Gobi Desert. July is the warmest month, and the average air temperatures in July are <15 ºC in the Altai, Khangai, Khuvsgul, and Khentii mountainous areas, +15 to +20 ºC in the valleys of mountainous areas, and +20 to +25 ºC in the southern part of the eastern steppe and the Gobi Desert (Batima et al., 2005). The extreme minimum temperature is -31.1 ºC to -55.3 ºC in January, and the extreme maximum temperature is +28.5 ºC to +44.0 ºC in July. The average annual precipitation amounts are 300–400 mm in the Khangai, Khentein, and Khuvsgul mountainous regions, 150–250 mm in the steppe, and 50–100 mm in the Gobi Desert. Approximately 85% of the total precipitation is observed from April to September, of which approximately 50–60% is in July and August (Batima et al., 2005), ranging from 38.4 mm in the extreme dry regions of the southern Gobi Desert to 389 mm in limited areas in the north. Approximately 90.1% of the rain water evaporates and only 9.9% constitutes the surface runoff, partially replenishing the groundwater aquifers.

The site is situated at an altitude of approximately 1100 m above sea level in the Orkhon-Tuul Mountainous Area of the Great Khangai Mountain region (Meteorological information of the

Bulgan province). The climate normative and parameter values were obtained from two of the nearest weather forecast stations to the Mural of the Shoroon Bumbagar, located in Bulgan aimag's Gurvanbulag and Bayannuur soums. The climatic conditions were determined by the differences in the day and night temperatures and were characterized by long winters and short summers, with highest precipitation in summer. Summer is dominated by warm dry air, and thunderstorms are expected during this season. The average annual temperature at the site is +11.8 °C, and the total annual precipitation is approximately 238.8 mm. In summer, the maximum air temperature is +37.0 °C, and the average annual precipitation is 229.0 mm, with a daily maximum precipitation of 45 mm. The mean annual wind speed is 10–12 m/s, and the annual wind speed is 10 m/s.

2.5 Summary

The Shoroon Bumbagar tomb is located on the southern slope of the Maikhan Mountain at an altitude of approximately 1100 m above sea level in the Great Khangai Mountain region. The underground tomb is composed of a burial chamber, four rectangular airshafts, and an open dromos, and the horizontal length from the entrance of the dromos to the back wall of the burial chamber is approximately 42 m. Most of the walls contain mural paintings. The climate of the territory where the Shoroon Bumbagar tomb is situated is similar to other regions of Mongolia, with large annual and daily temperature variations, extremely long as well as cold and dry winter, and short warm summer. The climate classification is typical continental climate. Natural saline formation are widely distributed on the site. Based on the geological surveys, the landform of the area is apparent, that is, 0–0.5 m below the ground level is the dark fertile topsoil layer containing plant roots and humus, at 0.5–1.5 m below the ground level is the light gray clay altered schist soil layer, and below 1.5 m is the light green and grayish blue sand-filled weathered schist alluvial formation. In other words, the walls of the open dromos are formed by three different soil layers. However, the airshafts and the burial chamber of the Shoroon Bumbagar tomb are located across two basement layers in the alteration zone, which constitute light green and light gray clay weathered schist layers.

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Chapter 3. Investigation of materials used in the Shoroon Bumbagar mural paintings

3.1 Introduction

An underground tomb with mural paintings was first discovered in Mongolia. Since the discovery of the tomb, the pigments and materials used in mural paintings have not been investigated. Although the mortar composition used in the mural painting was previously examined (Margottini, 2013), it was not clear from where the mortar samples were retrieved. Therefore, a detailed investigation is needed. The study of the mural layers as well as their characteristics provide basic information for the identification of the damage to the mural and development of methods for its preservation. Therefore, the aim of this chapter is to determine the structures of the mural paintings of the Shoroon Bumbagar tomb and the composition of the mortar and pigments used in the mural paintings.

3.2 Samples

The samples are listed in Table 3.1. To investigate the materials used in the mural paintings of the Shoroon Bumbagar tomb, two samples (SHB 1 and SHB 3) were collected from the fragments of the mural painting stored in the Kharakhorum Museum. In addition, one sample (SHB 2) was collected from the wall of the burial chamber. One section of the mural painting, which was located in the fourth airshaft, northwest corner, and inside the burial chamber collapsed face down after excavation in 2011. The fallen fragments of the mural paintings were retained during storage at the Kharakhorum Museum. Furthermore, to investigate the mural layer, three samples (CH 21, CH 23, and No. 10) were collected from the wall of the open dromos and burial chamber.

The mortar samples of the Shoroon Bumbagar mural painting were randomly collected from six different locations. Each sample was numbered as No. 1, No. 2, No. 3, No. 5, No. 6, and No. 7. Samples No. 5, No. 6, and No. 7 (Figure 3.1) were collected from the western wall of the open dromos area. Owing to the damage to the wall painting, the mortar collapsed and the bottom of the wall had accumulated, and mortar samples No. 1, No. 2, No. 3 (Figure 3.1), and No. 7 (Figure 3.2) were collected from the fallen one on the floor.

Table 3.1 Samples of the mural painting of the Shoroon Bumbagar tomb

		
SHB 1 (Red color)	SHB 2 (Red color)	SHB 3 (Red color)

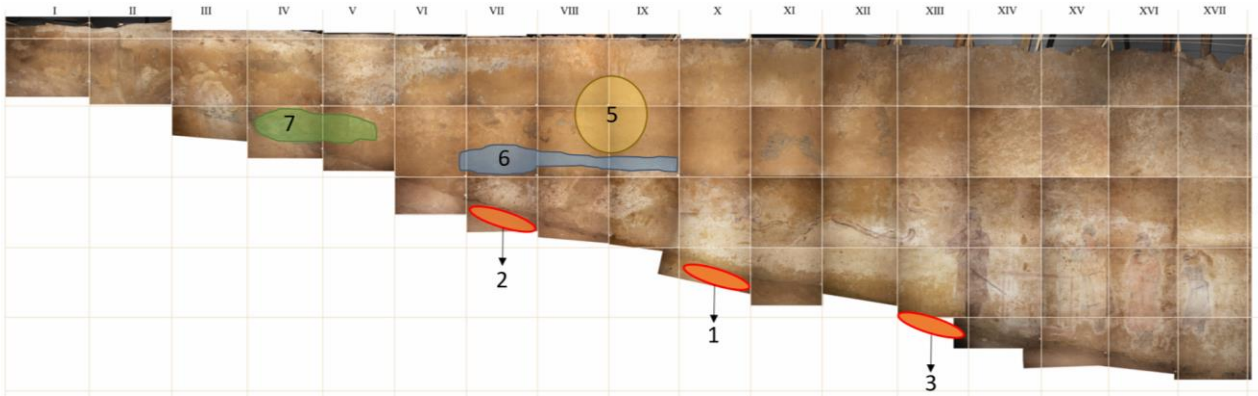

Figure 3.1. An image showing the location of the sample, west wall of the open dromos.

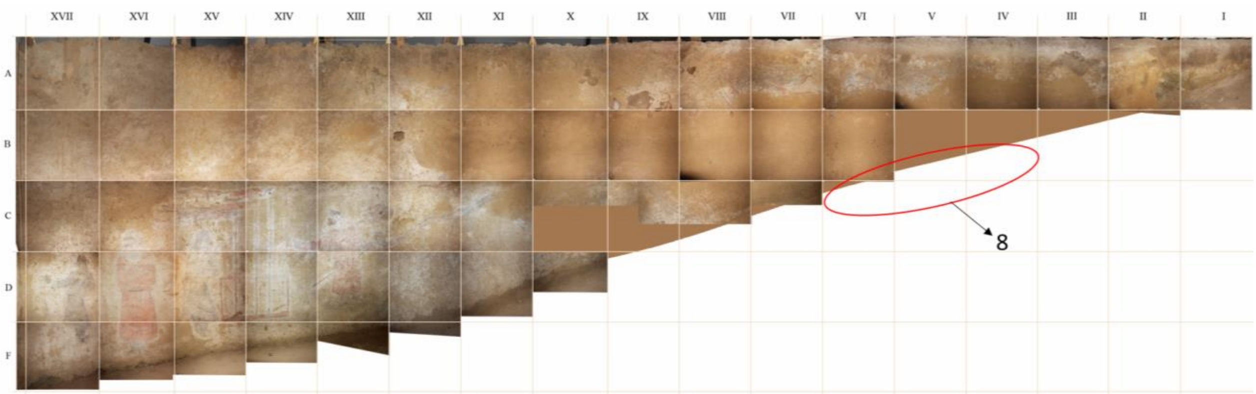

Figure 3.2. An image showing the location of the sample, west wall of the open dromos

3.3 Analytical methods

3.3.1 Optical microscopy

Surface appearance and shape of pigments were observed with use of stereo microscopes (Leica Z16 APOA, Leica MZ16). Observation distance from Objective lens to an object was 30 to 150 mm, and magnification was 10 to 120.

3.3.2 Soil particle size analysis

Particle size of mud plaster was analyzed at laboratory of soil investigation, school of Geology and Mining, Mongolian University of Science and Technology following ASTM D422.

3.3.3 X-ray fluorescence analysis (XRF)

Elements of plaster and pigments of the mural paintings were measured by two types of X-ray fluorescence analyzers. For the samples from fragments of mural paintings, desktop type analyzer, EDAX EAGLE III was used. The conditions of the measurement with the former instrument were followed: molybdenum target, tube voltage and current set to 40 kV and 30 μA respectively, and acquisition time 100 sec.

3.3.4 X-ray diffraction analysis (XRD)

The plaster and pigments of the murals were identified consequently by XRD, Rigaku Smartlab. The measurement conditions were followed: Cu-K alpha radiation, tube voltage 40 kV, tube current 40 mA and the scan range (2θ/θ) 5 to 90°.

3.4 Results and discussion

3.4.1 Structure and preparation layer

The layer structures of the murals have transformed over time depending on the materials used for their construction. Some murals have many layers of mud and paint. The structure of a mural can be generally classified as follows:

- Base wall or supporting wall, conglomerate
- Mortar layer (mud plaster)
- Fine plaster layer
- Ground layer
- Paint layer

In the Shoroon Bumbagar tomb, metamorphic rocks form the base wall. However, a conclusion regarding the structure of the mural that consists of the mortar and paint layers has not yet been reached. In particular, in the study “Excavation research on tombs of ancient nomad,” it was mentioned that to draw a painting, the bare rough stone surface was repaired and plastered with a mortar of 0.5–1.0-cm thickness, containing straw and chalk (Ochir et al., 2013, p.222). In addition, the layer thickness and its characteristics were described in “Cultural monuments of ancient nomads,” stating that a mortar thickness of 0.5 cm was applied (MAS, 2017). In the UNESCO report by a specialist, the thickness of the mortar was determined to be 0.5–4.0 cm.

Based on the research conducted by our team, sample No. 10, which was collected from the east wall of open dromos, consisted of three layers, that is, a paint layer (0.1 mm), ground layer, and mortar layer of approximately 1-cm thickness (Figure 3.3).

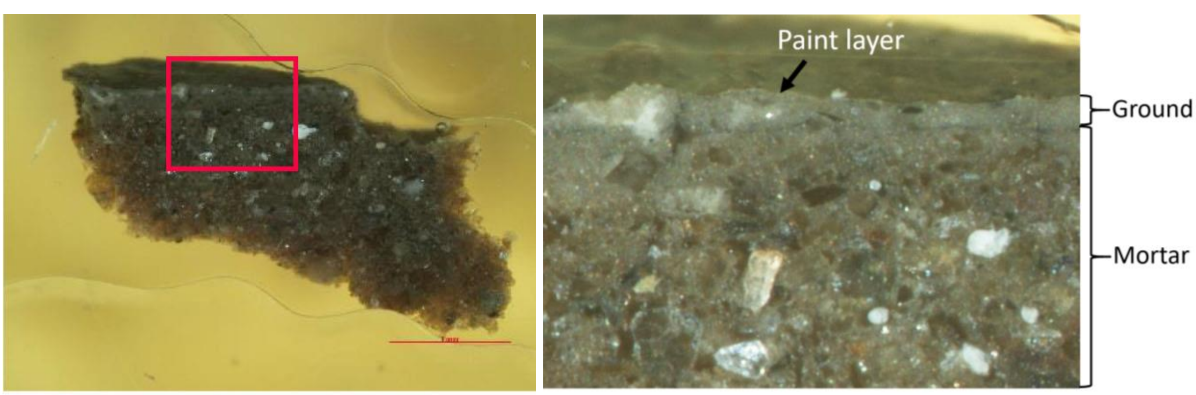

Figure 3.3. No.10, grey paint sample

In addition, sample CH 21 had a paint layer with 0.1-mm thickness and a mortar layer (Figure 3.4). Sample CH 23 from the burial chamber had paint layers with 0.04-mm thickness and a mortar layer (Figure 3.5). Based on the abovementioned results, the structure of the wall of the open dromos was different from that of the wall of the burial chamber. The mural painting of the open dromos had three layers, while the mural painting of the burial chamber had two layers, and the mortar thickness was 0.6–6.0 cm.

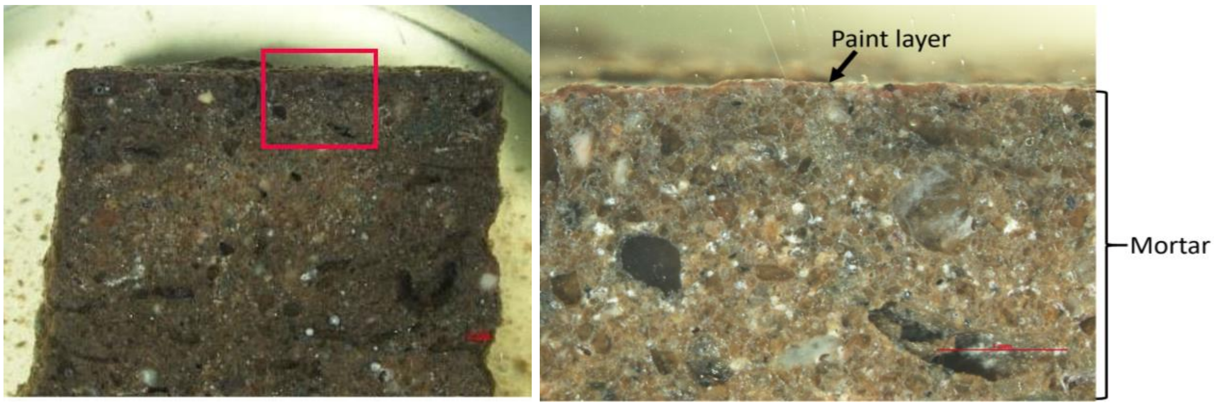

Figure 3.4. Sample CH 21, red paint sample

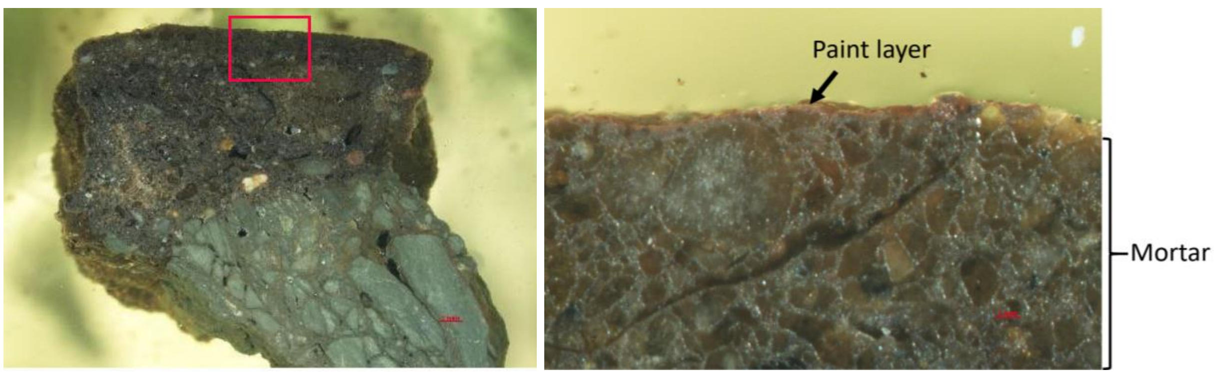

Figure 3.5. Sample CH 23, red paint sample

The mortar was identified under the UNESCO project of the Shoroon Bumbagar tomb. The report showed that the mortar used in the tomb was composed of quartz and feldspar, with a minor part of clay such as chlorite and illite (Figure 3.6) (Margottini, 2013).

In this study, the particle composition of the six mortar samples collected from different locations were analyzed. Based on the results of the experiments to determine the particle composition, it was confirmed that each sample comprised gravelly muddy sand. Using a specimen comprising one type of material, the average composition of the six samples was determined as 1.4% gravel, 51.2% sand, and 47.3% silt and clay (Table 3.2 and Figure 3.7). In addition, the clay content in the material was <5%.

This is consistent with the results described in the report "Bayannuur tomb: geo-mechanical condition and issue on storage of mural" by Margottini. He noted that the mortar of Shoroon Bumbagar tomb contained approximately 5% clay, and this low amount allowed the adhesion of mortar and additional organic binding materials (e.g., egg or milk protein) and naturally derived whey that could have been used (Margottini, 2013).

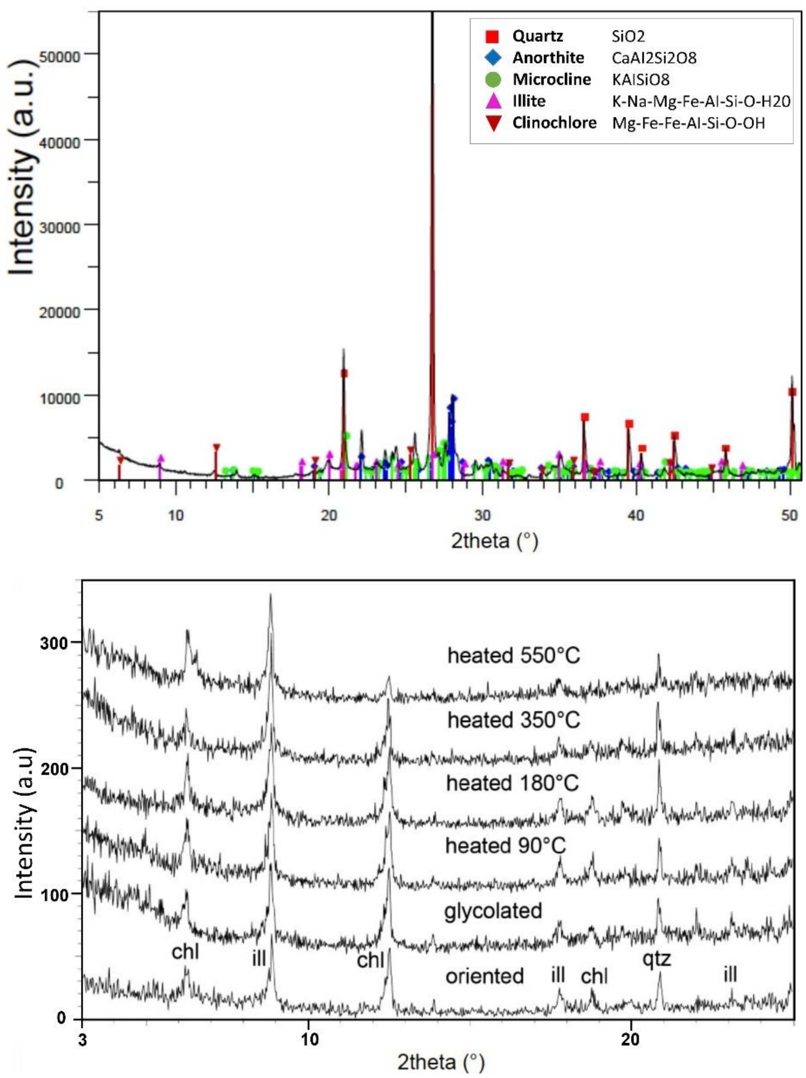

Figure 3.6. XRD analysis result of the mortar sample. This is mainly composed by quartz and feldspar. Identification of clay minerals in the mortar, this is composed by Clorite and Illite species. (© Margottini)

According to the computed tomography analysis of the Nara National Research Institute for Cultural Properties of Japan, straw was added to the mortar layer (Figure 3.8) (Angaragsuren & Kohdzuma, 2018). Moreover, the mortar layer contained a large empty space, that is, it was a porous structure. This porous structure resulted from the removal of the organic materials through decomposition for a long time. Furthermore, the amount of clay component was less, and the plasticity of the putty was low, which indicated that the adhesion in the base wall was low. Based on this data, it is inferred that the structure and mortar of the Shoroon Bumbagar mural painting are highly fragile and could be easily lost and cohere under humid conditions. Prior investigations have determined that mortar is fixed on a poor bedrock that can easily collapse and build via cohesion due to dryness. It is fragile, susceptible to direct water contact, and prone to breakage and deformation upon application of stress (Margottini, 2013).

Table 3.2. Particle size distribution of the mortar

Sample No.	Sample name	Mortar description-UCS system	Particle size distribution, %		
			Gravel	Sand	Silt, clay
1	Mortar	gSC Clayey sand with gravel	3.3	50.1	46.6
2	Mortar	gSC Clayey sand with gravel	1.3	53.9	44.9
3	Mortar	gSC Clayey sand with gravel	1.2	44.3	54.6
4	Mortar	gSC Clayey sand with gravel	0.8	54.5	44.7
6	Mortar	gSC Clayey sand with gravel	1.0	56.5	42.5
8	Mortar	gSC Clayey sand with gravel	0.9	48.3	50.8
Average			**1.4**	**51.2**	**47.3**

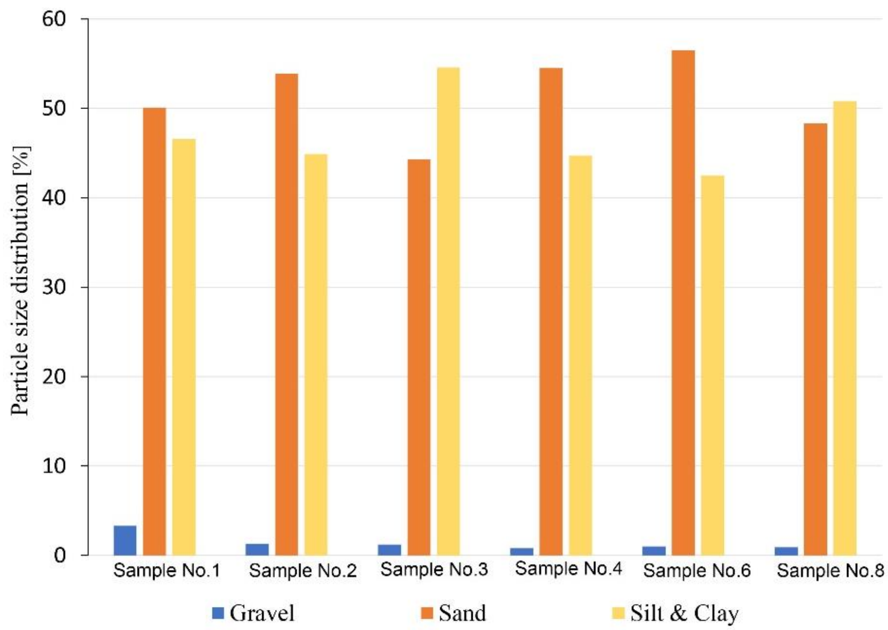

Figure 3.7. Particle size distribution of the mud plaster

3.4.2 Pigments and paint layer

In this study, only red and light red pigments used in the mural paintings of this tomb were identified. The identification of the pigments used in the mural paintings of the Shoroon Bumbagar tomb was difficult because physical deterioration by a white precipitate and discoloration were observed on the surfaces of the walls. Therefore, in this study, the results obtained for the two samples that were not previously analyzed are reported.

The mural painting had a base mortar, ground layer, and paint layer. For elemental analysis, red pigments in the samples, ground, and mortar were identified. The results of the X-ray fluorescence analysis are listed in Table 3.3. Fe, Ca, Si, K, S, Al, and Ti were found in the samples. A high Fe content was detected in the red pigmented areas of all samples, whereas mortar contained a high Si content. In addition, a high Ca content was detected in the ground area (Angaragsuren & Kohdzuma, 2020).

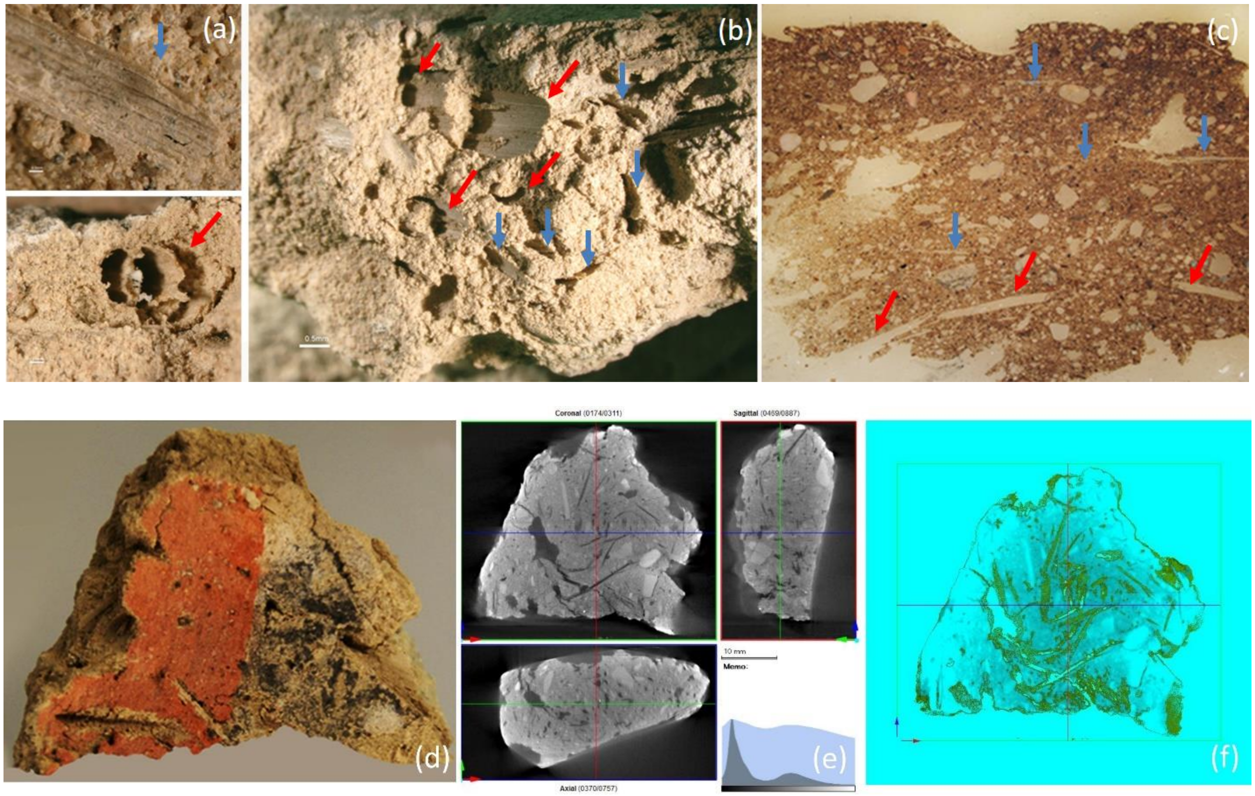

Figure 3.8. Microscope and scanning electron micrographs of the straw in mortar. a) The image of the straw, b) Micrographs of the straw, c) The cross-section of the mortar, d) the picture of the mural painting sample, e) Computed tomography scanning image, f) CT image of straw inside the mural painting

Table 3.3. List of samples taken from the wall paintings of the Shoroon Bumbagar tomb. Their color and results were obtained by XRF.

Sample name	Identified points of the sample			Elements determined by XRF
SHB 1	Red	-	-	Fe, Si, Ca, K, Al, Ti
SHB 2_01	Light red	-	-	Fe, Ca, Si, K, S, Al, Ti
SHB 2_02	-	-	Mortar	Si, Fe, Ca, K, Al, Ti, S
SHB 3_01	Red	-	-	Fe, Ca, Si, K, S, Al, Ti
SHB 3_02	-	Plaster	-	Ca, Fe, Si, K, Al, S, Ti
SHB 3_03	-	-	Mortar	Si, Fe, Ca, K, Al, Ti, S

The identification of the components in the materials using X-ray diffraction (XRD) depends on the XRD pattern obtained from the interaction with the crystalline structure of the material. XRD was used to identify the compounds present in the paint and plaster layers, particularly, the red pigment in samples SHB 1 and SHB 2, and light red pigment in SHB 3.

Based on the results obtained from the mineralogical analysis of the samples by XRD, hematite (Fe_2O_3), calcite ($CaCO_3$), and quartz (SiO_2) were found in Sample SHB 1. However, a large amount of calcite was detected in the light red pigment of Sample SHB 3_02, which was probably a mixture of hematite and calcite. In addition, calcite and quartz were found in Sample SHB 2.

3.4.3 Characteristics of the Shoroon Bumbagar mural painting

The investigation of the materials used in the mural of the Shoroon Bumbagar tomb showed that the mural of the burial chamber had two layers containing paint and mortar layers. In addition, a thin mortar layer was applied to the base wall of the open dromos. However, the mural of the burial chamber had different thicknesses of the mortar layer.

It was evident that the structure of the underground tomb and the motifs of the mural paintings were significantly influenced by the burial rituals of the Tang dynasty. The results of some studies (Mangmang, Yongjian, 2010; Zuixiong, 2010; Guoxin et al., 1993) showed that many pigments were used during the Tang dynasty period. However, the excavation report (Ochir et al., 2013) of the Shoroon Bumbagar tomb and the project report of the preservation and conservation of this ruin (Lunsford, 2012) indicated that red, brown, black, and blue pigments were used in the mural paintings of the Shoroon Bumbagar tomb. During the field survey, a limited palette including brown, light red, red, and black colors was found in the mural painting; in particular, only red and black pigments were used in the painting. In this study, only red and light red pigments used in the mural painting of this tomb have been identified.

3.5 Summary

The main aim of this study was to determine the structures, mortar compositions, and pigments used in the mural paintings of the Shoroon Bumbagar tomb. The pigments and mortar layer used for the Shoroon Bumbagar mural paintings can be summarized as follows.

- The mural painting of the open dromos of the Shoroon Bumbagar tomb has three layers, that is, paint, ground, and mortar layers. The mural painting of the burial chamber consists of two layers.
- The red pigment used in the mural paintings of the Shoroon Bumbagar tomb is hematite (Fe_2O_3), and the ground layer is calcite ($CaCO_3$). It is necessary to further investigate the materials in brown, black, and blue pigments used in this tomb.
- The particle composition of the mortar used in the Shoroon Bumbagar mural comprises 1.4% gravel, 51.2% sand, and 47.3% silt and clay. In addition, the clay content in the material is <5%.

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Chapter 4. Deterioration of the Shoroon Bumbagar mural paintings

4.1 Introduction

Some conservation activities were carried out to preserve the mural paintings of the Shoroon Bumbagar tomb after an archaeological excavation. The first step of the preventive conservation was to protect the detachment and collapse of the mural paintings by freezing during winter. Thereafter, the surface of mural was covered with cotton textile and bags filled with sand (Altynbekov, 2014; Lunsford, 2012). Unfortunately, a year later, all the sandbags were removed because there were signs of mold growing on the surfaces of the mural paintings. Except for the above damage, no severe damage was observed within the tomb, and the mural paintings were preserved in relatively good conditions. Although many conservation activities were carried out from 2012 to the present, the mural paintings continued to deteriorate. The most important factor is the determination of the type of damage that occurs in each part of the tomb. It is necessary to determine the cause and effects of these deteriorations on the mural paintings.

This chapter describes the investigation of the mural painting deterioration, the distribution of the damaged areas of the mural paintings according to seasonal weather changes, and a summary of the deterioration factors affecting the mural paintings. During the archaeological excavation, a polythene sheet tent was built over the tomb to provide temporary protection from exposure to rain, wind, and direct solar radiation. After the archeological excavations, the tomb murals were found to be well preserved. Subsequently, it was decided that all mural paintings should be preserved on-site. A metallic permanent shelter with dimensions of 45 m × 12 m was built above the tomb after completing the archaeological excavation in 2011. Although it was built to protect the tomb against external impact, the deterioration was confirmed to be caused by several factors. The factors affecting the burial chamber, airshafts, and open dromos are discussed under the following conditions.

4.2 Lack of cohesion of the bedrock

A lack of bedrock cohesion led to damages such as the scaling of the mural paintings in the burial chamber and some parts of the airshafts (Figure 4.1). The tomb is located in the alteration zone, with light green and light gray clay weathered schist and phyllite layers. The top ground is a dark, fertile topsoil layer containing plant roots and humus (described in Chapter 2). Margottini studied the test rock mechanics classification and rocky mass strength of the Shoroon Bumbagar tomb using geological strength index (GSI), tunneling quality index (Q-Index), and rock mass rating (RMR) system. All classifications clearly showed inferior material. The metamorphosed rock of the Shoroon Bumbagar tomb is of very poor quality (Margottini, 2013). Thus, the mural painting bedrock is at a risk of collapse as the tomb is located in a highly vulnerable and sophisticated geological setting.

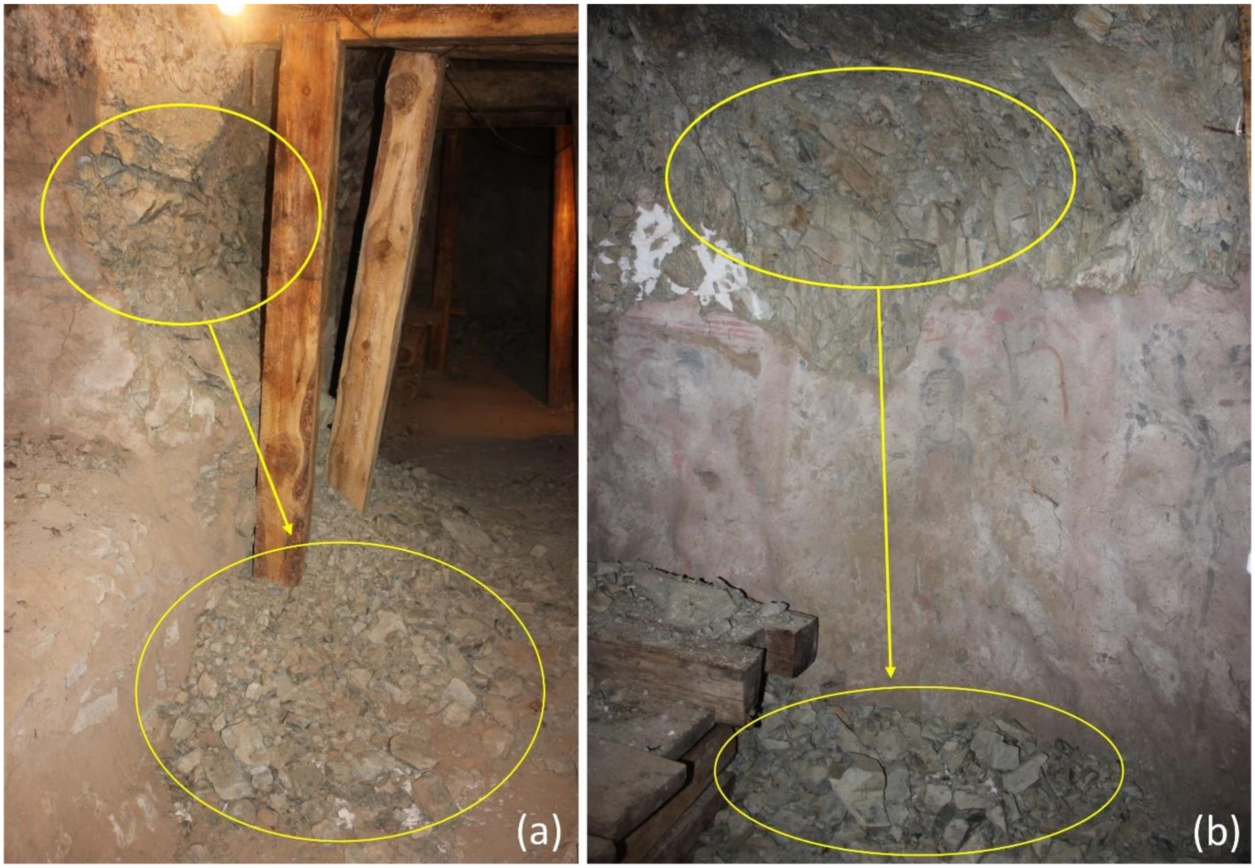


Figure 4.1. a) A lack of adhesion and cohesion of bedrock inside the airshaft. b) burial chamber

4.3 Fungal growth on the wall surface

Passages, airshafts, and burial chambers showed fungal growth on the mural paintings and wooden supports (Figure 4.2). The next colossal deterioration of the mural painting constitutes the fungal growth, and its cause is described as follows. In 2012, fungal growth was observed on the surfaces of the mural paintings for the first time. After the first preventive conservation within the Shoroon Bumbagar tomb (Chapter 2), signs of mold growth on the surfaces of the mural paintings were observed. Except for this damage, no severe damage was observed within the tomb and mural paintings, and the preservation conditions were suitable. The UNESCO report by expert, Lunsford, stated that the coverage of the surfaces of the mural paintings with cotton textile and bags of sand did not allow the natural water vapor exchange from the interior of the subsoil with the surface and vice versa, which increased the humidity near the surface of the render, promoting the concentration of water. The function of the sandbags was to prevent the collapse of the renders by freezing during winter. This operation was ineffective because the subsoil was not considered to be warm in winter due to the retarded flux of the heat that warmed the ground during last summer. Therefore, the exposed renders did not freeze in winter and did not collapse. The mural paintings were covered and stained by microorganisms because of the coverage of the surface with cotton textile and sacs filled with sand that trapped humidity, leading to microbial attack (Lunsford, 2012, p.11). Considering these occurrences, it was speculated that fungal growth on the mural painting surfaces was caused by inappropriate conservation and preservation processes. Fungal growth eventually stopped, and no further growth was observed on the mural paintings after these were placed in normal conditions by removing the sand-filled sacks in front of the wall. Currently, the fungal colonies have grown on wooden supports and only spread into the nearby mural painting areas. The main factors responsible for fungal growth include temperature, humidity, oxygen, and nitrogen levels. A specialist from the Cultural Heritage Center carried out annual surface cleaning of the mural paintings. However, this did not completely prevent the growth of the microorganisms. It is assumed that organic materials, lack of adhesion and cohesion, and appropriate humidity create a favorable environment for fungal growth.

Consequently, the determination of the humidity level in the internal environment is required through environmental studies in the burial chamber and airshaft areas. In 2012, the wooden props that these supports were almost entirely covered by microorganisms (Lunsford, 2012, pp.9-10). Each year, Center of Cultural Heritage (CCH) carries out wet and dry cleaning of the microorganisms of the wooden propping, bedrock surface, and surfaces of the mural paintings, which is not an effective activity. Many factors such as temperature, humidity, oxygen concentration, nutrients, and pH affect the growth of fungi and molds.

In 2017, we analyzed the preservation conditions of the mural paintings kept in the museum and in the original location using scanning electron microscopy. After the tomb excavation was completed, some of the collapsed murals were transported to the Karakorum Museum in 2011. One sample (CH-1) was collected from the burial chamber and another was obtained from the storage room of the Kharakhorum Museum. The result showed the proliferation of subaerial biofilm microbes on the surfaces of sample CH-1 (Angaragsuren, 2017; Angaragsuren, & Kohdzuma, 2018) (Figure 4.3). Sample KH 1, which was preserved in the storage room of the Kharakhorum Museum under investigation, was found to be in good condition (Figure 4.4).

Figure 4.2. Fungus developing on surface of the mural painting in the airshafts and burial chamber

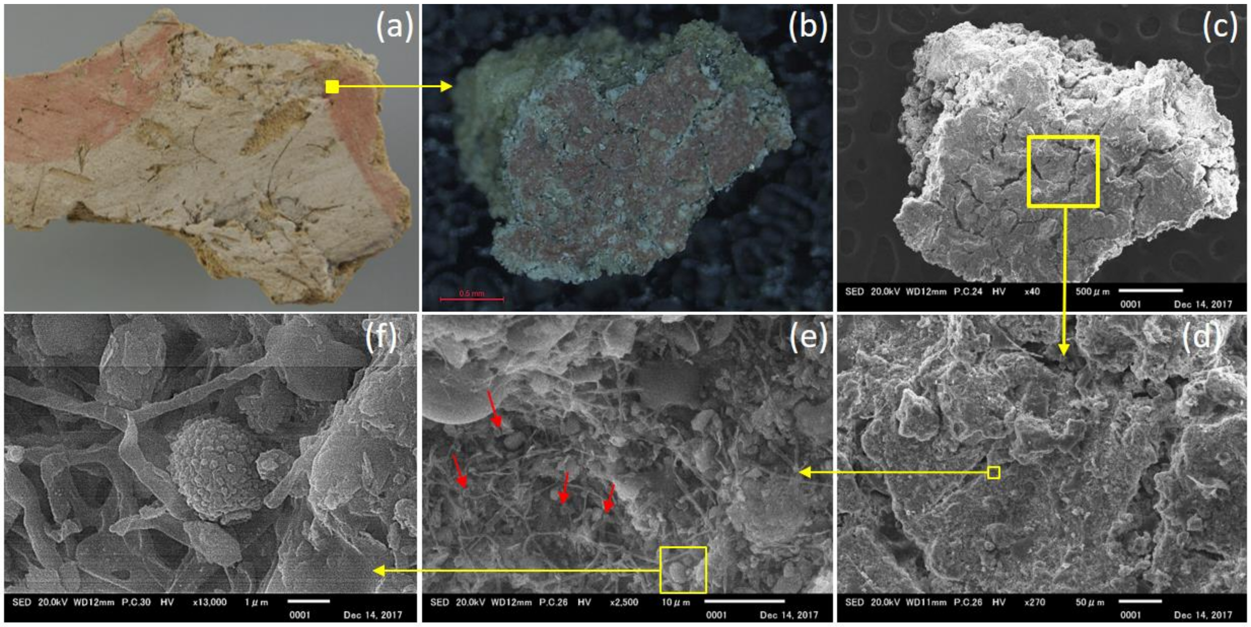


Figure 4.3. Microscope and scanning electron micrographs of the burial chamber sample. a) Picture of the sample, b) Microscope picture, c) Scanning electronic micrographs, magnification x40, d) Scanning electronic micrographs, magnification x270, e) Fungal growth on the sample, SEM magnification x2500, f) SEM magnification x13000

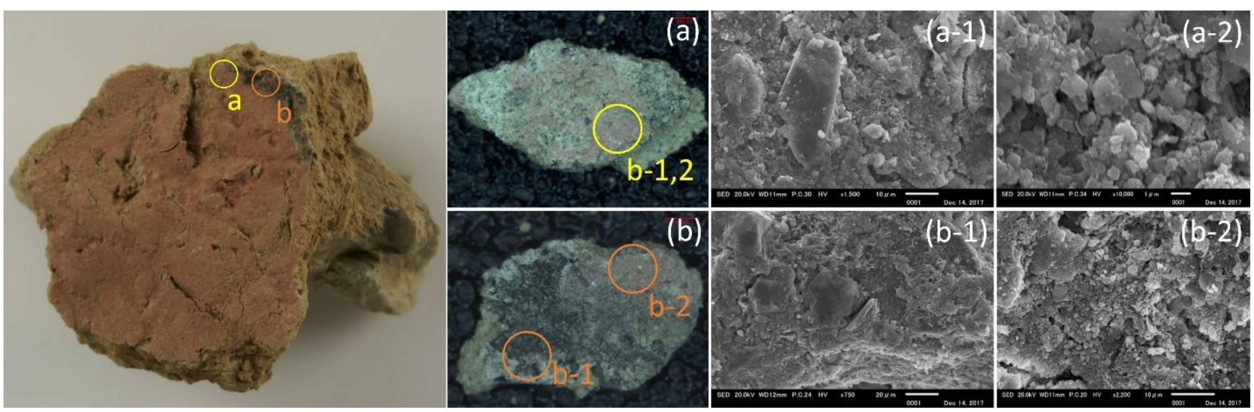


Figure 4.4. Microscope and scanning electron micrographs of the Kharakhorum museum sample. a) Picture of the sample, a-1) Scanning electronic micrographs of red color, magnification x1500, a-2) Scanning electronic micrographs of red color, magnification x10000, b-1) Scanning electronic micrographs of black color, magnification x750, b-2) Scanning electronic micrographs of red color, magnification x2200

4.4 Detachment and peeling of the preparatory layers (paint, ground, and mortar)

Detachment and peeling of the ground and paint layers as well as the mortar were observed on the surfaces of the west and east walls of the open dromos area and upper parts of the airshafts (Figure 4.5). An additional colossal deterioration process includes the flaking and scaling of the mural painting. Its causes are described as follows. For the preservation of the mural paintings in

2012, the detachment of the paint layer was observed for the first time in some areas of the mural painting of the open dromos. A summary of the results of the observation survey showed an area with the flaked paint layer on the western wall of the open dromos in 2014. In addition, based on the deterioration distribution on the walls during September 2017, a severe damage was observed in which the peeling of the mortar layer was detected.

Figure 4.5. Peeling of the mural painting in the upper part of the airshaft

4.5 Monitoring and documentation of the deteriorating areas of the open dromos

The paint, ground, and mortar layers of the wall paintings of the open dromos peeled off rapidly. Therefore, in this study, the deterioration was monitored with photographic documentation of the complete walls. The observation periods were March, September, and November 2017, January, March, and November 2018, January, April, June, August, and December 2019, and May 2020.

The open dromos was approximately 200-cm wide and 20-m long. The floor level was five meters below the ground level. As the first step of the monitoring and documentation of the deterioration area of the open dromos, photo documentation was required to record the preservation conditions. Each wall was subdivided into 100 cm × 100 cm grids, which were installed five centimeters above the surface of the mural painting using fitted threads (Figure 4.6). Each subdivided section was numbered horizontally from "I to XVII" (from the entrance to the north side) and vertically from the ground level to down as "A to D" (Figure 4.7). The subdivided parts were individually photographed for an extended interval to monitor the surface changes or deterioration processes and subsequently compared.

Figure 4.6. Preparation to photographic documentation

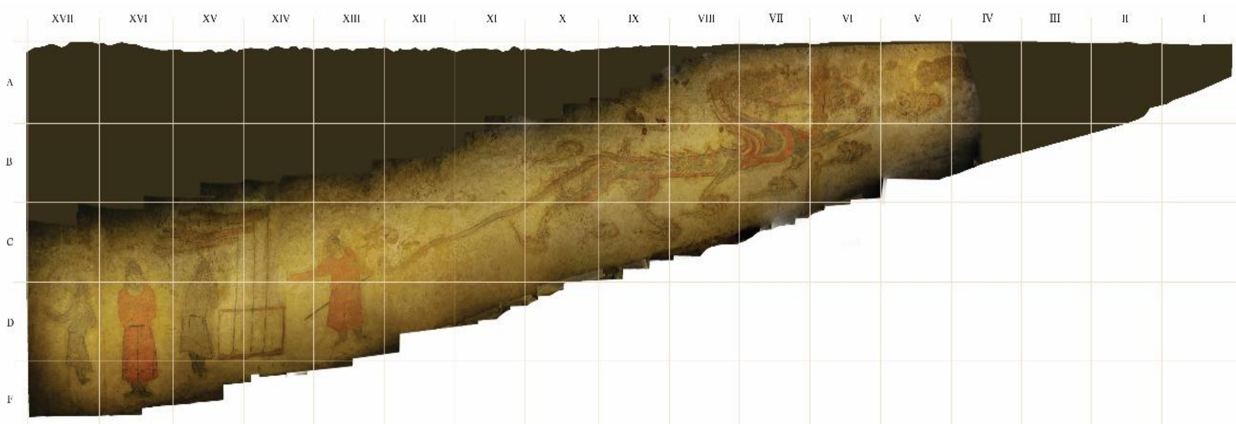


Figure 4.7. Horizontally and vertically subdivided parts on the wall (Eastern wall of open dromos)

In this section, the condition assessment and deterioration distribution of the mural paintings of the open dromos are presented. The deterioration process can be subdivided into the following three categories: orange, light blue, and red (Figure 4.8).

- Part I (orange) showed minimal deterioration in which peeling of the paint layer was observed in some places.

- Part II (light blue) showed that the paint and ground layers were lost, but there was no mortar layer loss.

- Part III (red) showed significant deterioration on the walls. The paint, ground, and mortar layers were completely destroyed. The underlying bedrock was visible.

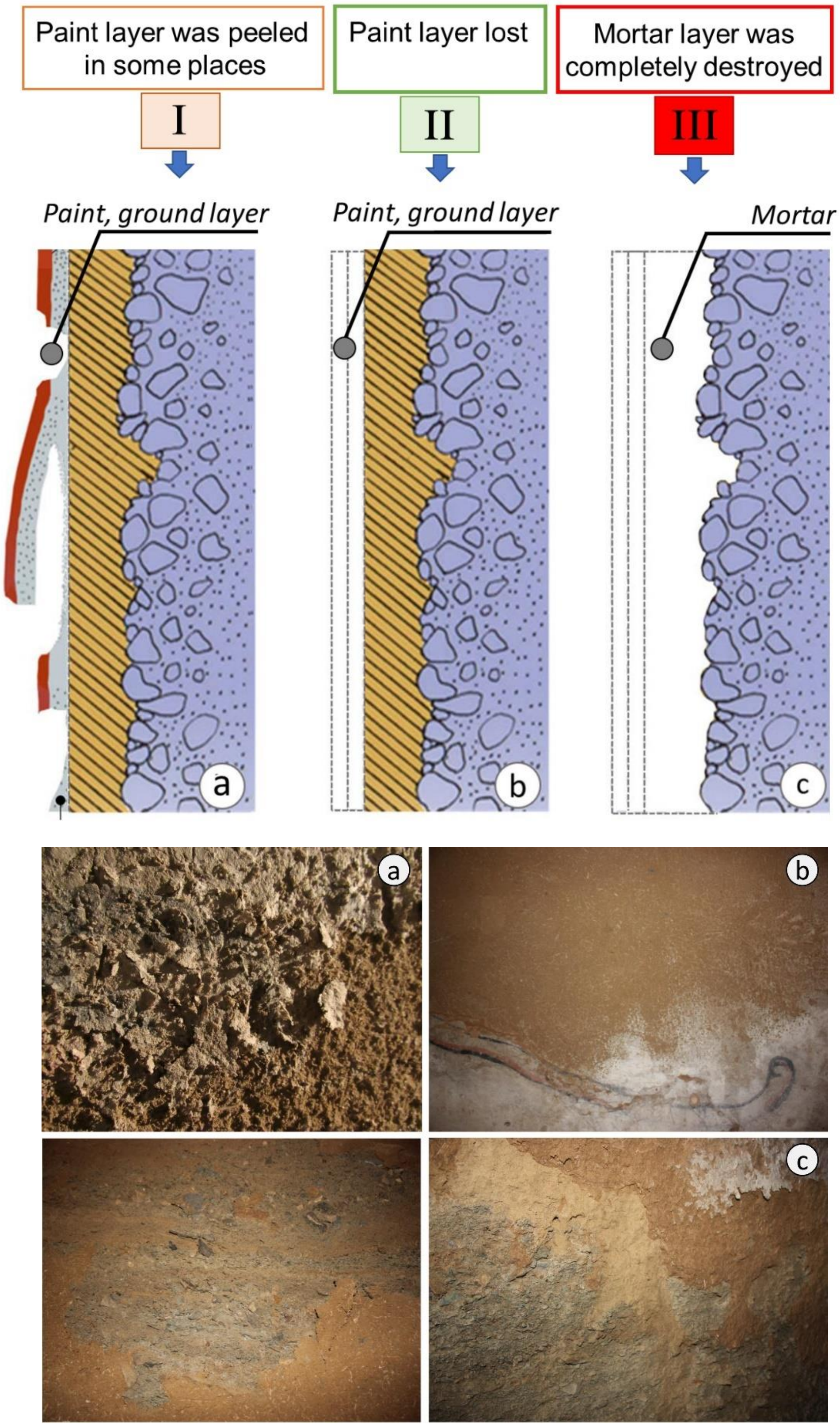


Figure 4.8. Mural deterioration. a) loss of the paint and plaster layer, b) Detachment c) Scaling process

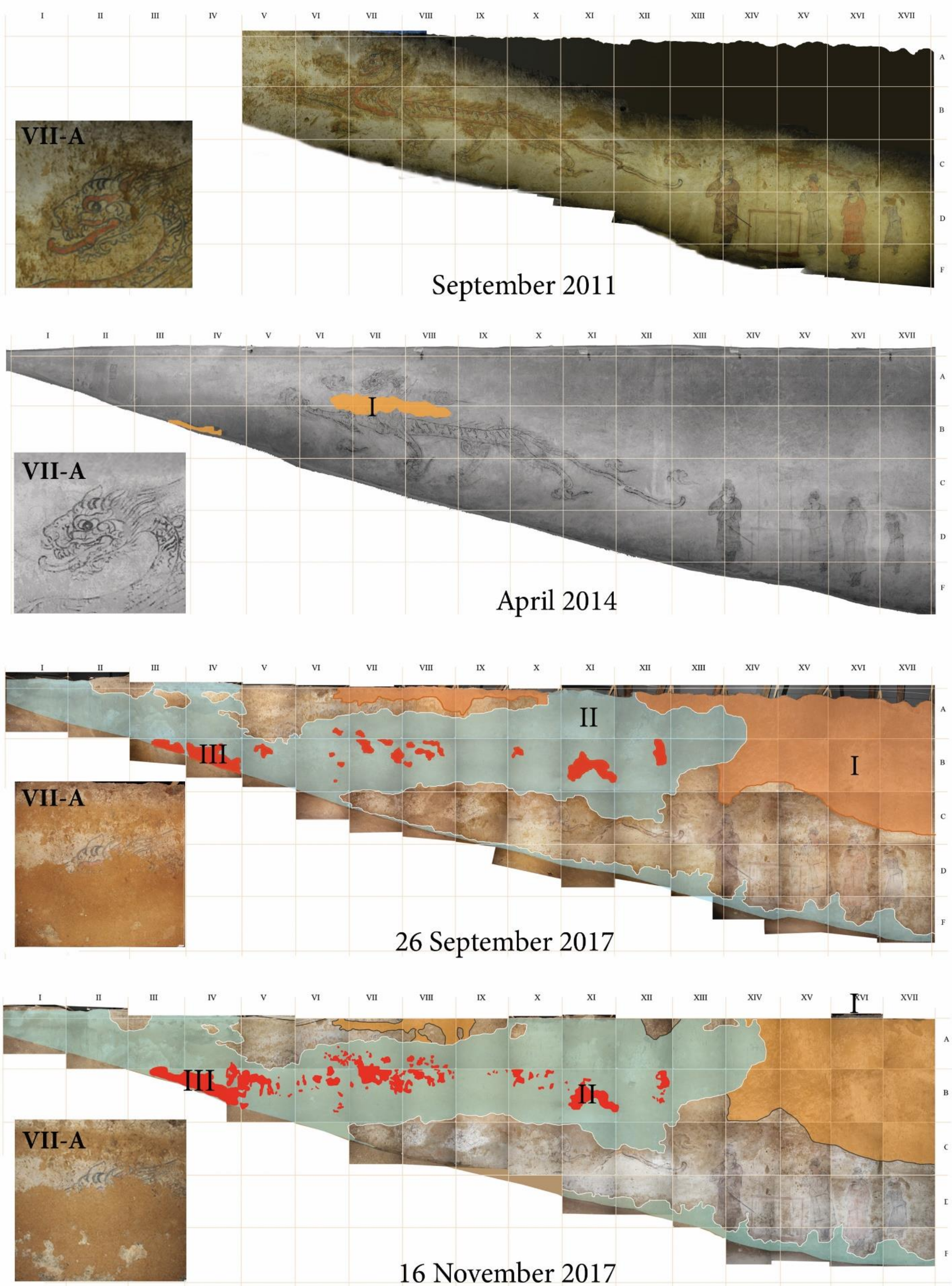
4.5.1 Condition assessment and deterioration distribution of the western wall

An observation survey was conducted by comparing the actual conditions with the previous photographic documentation. Based on a 3D photograph from 2014, it was observed that the pigment layer on some areas of the wall (VIIA section) was lost (Figure 4.9). In a photograph from September 2017, the paint layer peeling on the wall was spread from the ground level to the middle part (Figure 4.9). The area with lost paint and ground layers was distributed from section IA (near the entrance) to XIVA and XIVB. This type of deterioration was also observed in the lower parts of the wall. In other words, the paint and ground layers were entirely lost in this gird. The paint, ground, and mortar layers were completely destroyed in several girds (IIIB, IVB, VB, VIA, B, VIIB, XB, XIB, and XIIB), as shown in red. The second examination was carried out two months after the first observation.

In November 2017, the deteriorated parts were stable. Nevertheless, the area in which the paint, ground, and mortar layers were completely destroyed was distributed horizontally throughout the length of gird B. Based on the observation survey in January 2018, the orange and light blue parts did not change, but the red deteriorated area spread from IIIB to XA, XIIA, and XIIB. In November 2018, the paint layer peeling was detected in XVIB, XVIIA, and XVIIB. In addition, the red part was spread from IIIB to XIIA and XIIB. The examining of the deterioration condition in January 2019 showed that the orange and blue parts did not change. The light blue part was newly detected in XVIIB, and the red part spread horizontally throughout the length of gird B (IV to XII). In April and June 2019, the orange part did not show a change; the light green part was spread to several places from XIII to XVII.

4.5.2 Condition assessment and deterioration distribution of the eastern wall

The distribution of the eastern wall is shown in Figure 4.10. In 2014, no deterioration was observed. In September 2017, a peeled off paint layer was detected in some places on the middle part below the ground level. The light blue part spread from IA to XIII. Similar deterioration was observed in the lower parts of the eastern wall (Figure 4.10). According to the observation survey in January and May 2018, the orange and blue parts did not change. Nevertheless, the lost area of the mortar layer (red part) was spread from IA to VIA, VIB, and V IIIB to XIB. The orange and light blue parts did not change, and the red parts were slightly spread in VB, VIB, and VIA during November 2018 and January, April, and June 2019 (Figure 4.10).


I II III IV V VI VII VIII IX X XI XII XIII XIV XV XVI XVII
A
B
C
D
F
VII-A
September 2011
I II III IV V VI VII VIII IX X XI XII XIII XIV XV XVI XVII
A
B
C
D
F
I
VII-A
April 2014
I II III IV V VI VII VIII IX X XI XII XIII XIV XV XVI XVII
A
B
C
D
F
I
II
III
VII-A
26 September 2017
I II III IV V VI VII VIII IX X XI XII XIII XIV XV XVI XVII
A
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VII-A
16 November 2017

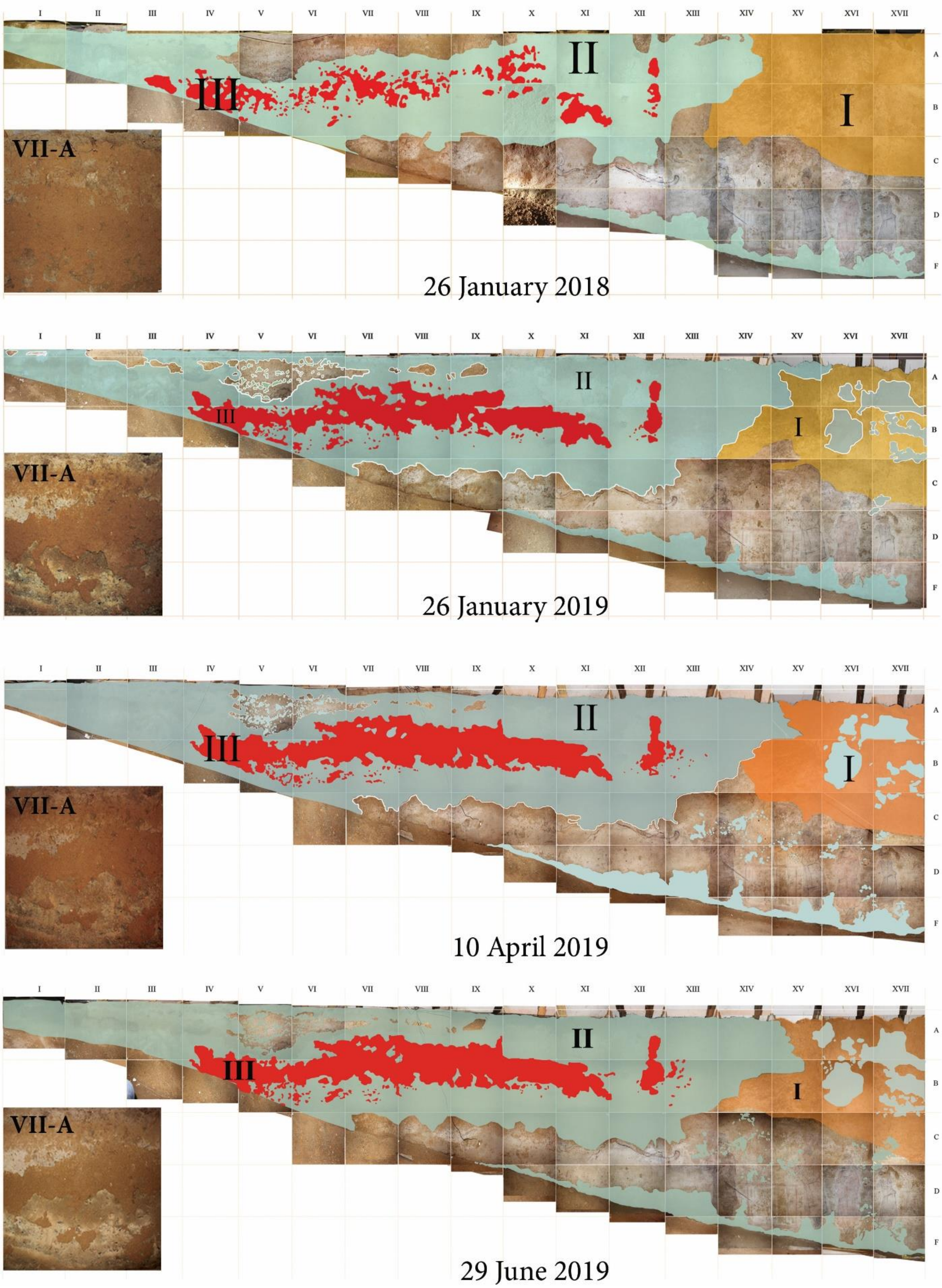
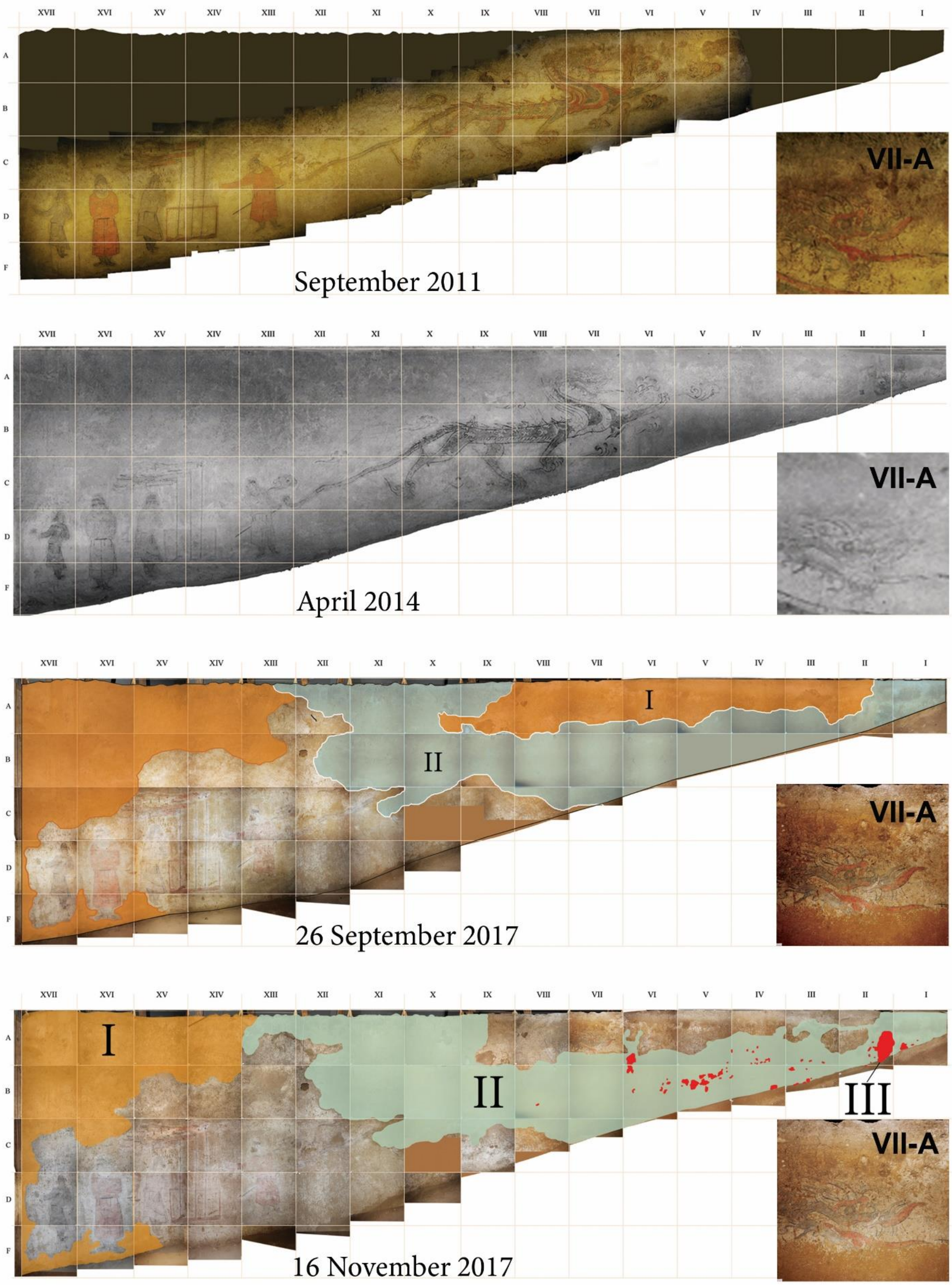


Figure 4.9. Condition assessment and deterioration distribution of the western wall


XVII XVI XV XIV XIII XII XI X IX VIII VII VI V IV III II I
A B C D F
VII-A
September 2011
XVII XVI XV XIV XIII XII XI X IX VIII VII VI V IV III II I
A B C D F
VII-A
April 2014
XVII XVI XV XIV XIII XII XI X IX VIII VII VI V IV III II I
A B C D F
I
II
VII-A
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VII-A
16 November 2017

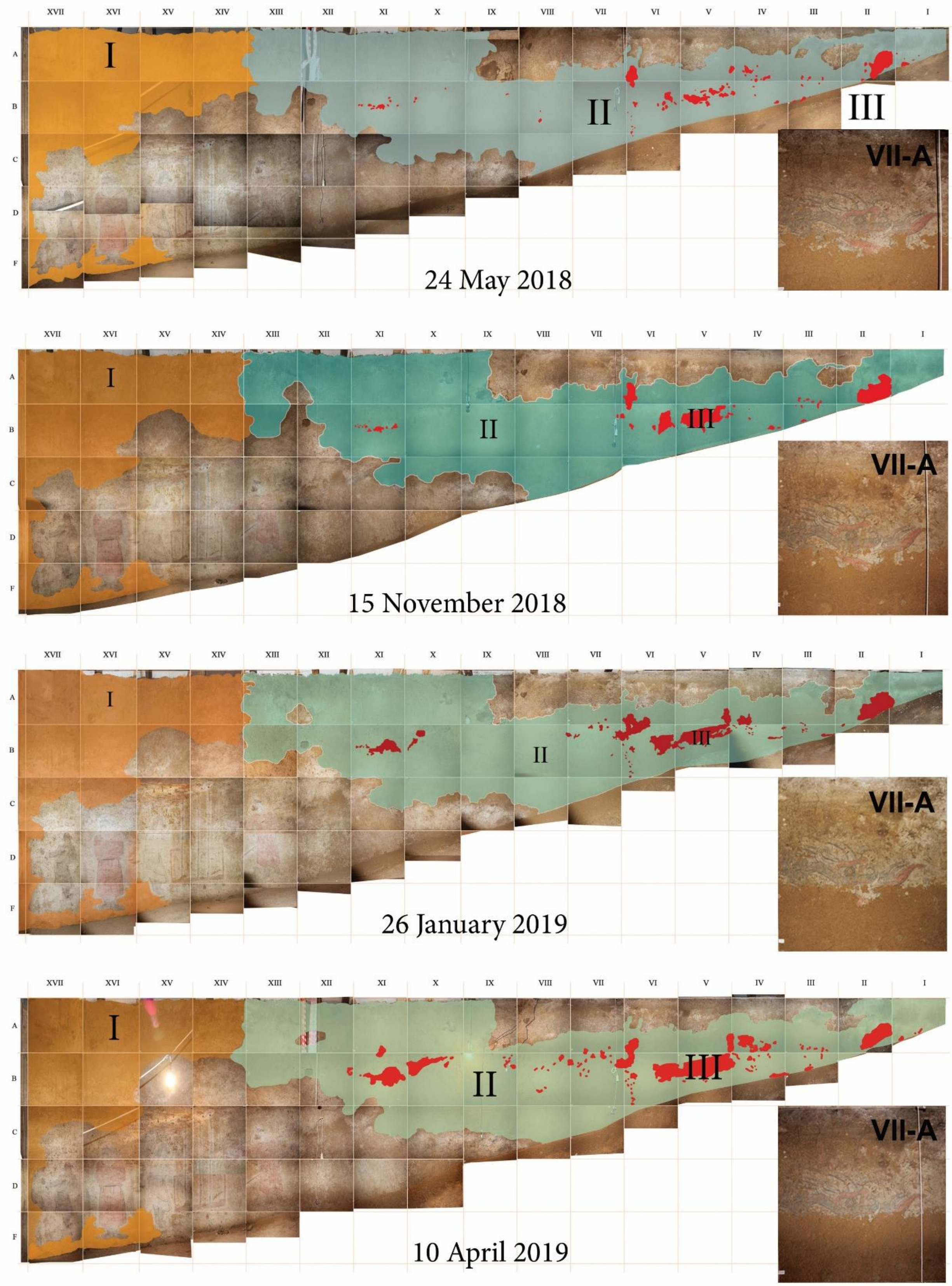

Figure 4.10. Condition assessment and deterioration distribution of the eastern wall

4.6 Deterioration due to salt precipitation

In the Shoroon Bumbagar tomb, the leading cause of the deterioration of the mural paintings was the salts that crystallized on the wall surface. White precipitation occurred on the west and east wall surfaces of the open dromos. A small amount of white precipitate was collected for identification using XRD analysis in 2017. The measurement conditions are listed in Table 4.1.

Table 4.1. Measurement condition for X- X-ray diffraction analysis

Tube voltage [kV]	40
Tube current [mA]	40
Scan range	(2θ/θ) 5 to 90°
Scan speed [deg./min]	2.0
Target	Cu-K alpha

White precipitates were identified as thenardite Na_2SO_4. Figure 4.11 shows the XRD data for the white precipitate found on the mural painting surfaces.

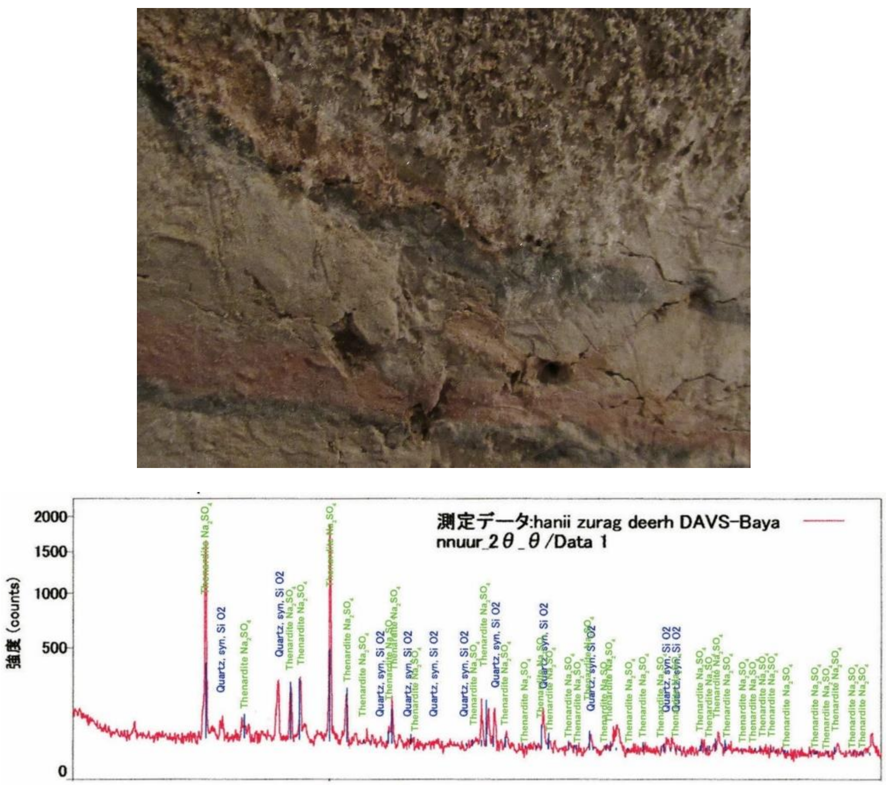

Figure 4.11. Salt precipitation on the wall in open dromos area and X-ray diffraction analysis chart of salt composition

Sodium sulfate is known to have two stable phases, thenardite (anhydrous) and mirabilite (decahydrate), and a metastable phase comprising heptahydrate. The equilibrium relative humidity of the mirabilite-saturated solution is approximately 93%. With a decrease in humidity, mirabilite gradually becomes less stable with respect to thenardite, and a phase transition occurs at approximately 75% RH at 20 °C. Another characteristic of sodium sulfate is the highly temperature-dependent solubility of mirabilite. At >32 °C, this salt is not stable; the humidity range in which it is stable increases with decreasing temperature (Robert J. Flatt, 2002).

Two main mechanisms are proposed below to explain the extensive damage caused by sodium sulfate.

Hydration pressure. Hydration results in a large volume expansion (approximately 314%) as the anhydrous phase of sodium sulfate (thenardite) converts into its decahydrate phase (mirabilite). The dissolution of thenardite can produce a solution that is supersaturated with respect to mirabilite, and precipitation from this solution (to form mirabilite and mirabilite-saturated solution) is associated with an increase in volume (Flatt, 2002). Thenardite converts into mirabilite through dissolution and reprecipitation. For such a mechanism, volume expansion may generate stress. The volume change associated with water-to-ice transition can induce damage through the evolution of hydraulic pressure (Flatt, 2002; Tsu et al., 2003; Scherer, 2004). The critical factors in generating hydraulic pressure are the volume changes. For example, sodium sulfate crystallization rate at 20 ºC is nine times lower than that for water freezing, and the crystallization rate is lower for mirabilite than for ice. Therefore, it is improbable that hydraulic pressure accounts for the damage caused by sodium sulfate crystallization.

Crystallization pressure. Deterioration due to salt crystallization is characterized by the local scaling of the surface, microcracking in mortar, loss of binder aggregate bonding and binder cohesion, and severe spalling (Thaulow and Sahu (2004) postulated that crystals growing under supersaturated conditions can exert high crystallization stress. These mechanisms were confirmed by Scherer, indicating that a salt crystal can exert pressure on the pore wall owing to the linear crystal growth from the supersaturated solution.

The above deterioration mechanism affects the open dromos of the Shoroon Bumbagar tomb. In other words, the main cause of the deterioration of the paint, ground, and mortar layers of the wall painting is the salt recrystallization in the open dromos and airshafts. Thus, in this study, the deterioration was monitored with photographic documentation of the complete walls. Sodium salt precipitation was monitored in eight girds (IIA, VA, VB, XIIB, XIIC, XIID, XVIIB, and XVIIF) on the western and eastern walls of the open dromos (Figures 4.12 and 4.13). During monitoring, photographs of the above girds were collected in September 2017, November 2017, January, May, and November 2018, January, April, June, and September 2019, as well as May 2020. The amounts of salt precipitation on the wall surfaces are listed in Tables 4.2 and 4.3. Salt precipitation was often observed in IIA, VA, and VB girds of the eastern wall near the entrance from January to April. XVIID did not show any salt precipitation. Salt precipitation distribution in the western wall was spread from IIA to XVIIB between September and June. Efflorescence was observed on VB and XIIB. The most active seasons were November and January, and the precipitate formed needle-like crystals that were identified as sodium sulfate (Figures 4.12 and 4.14).

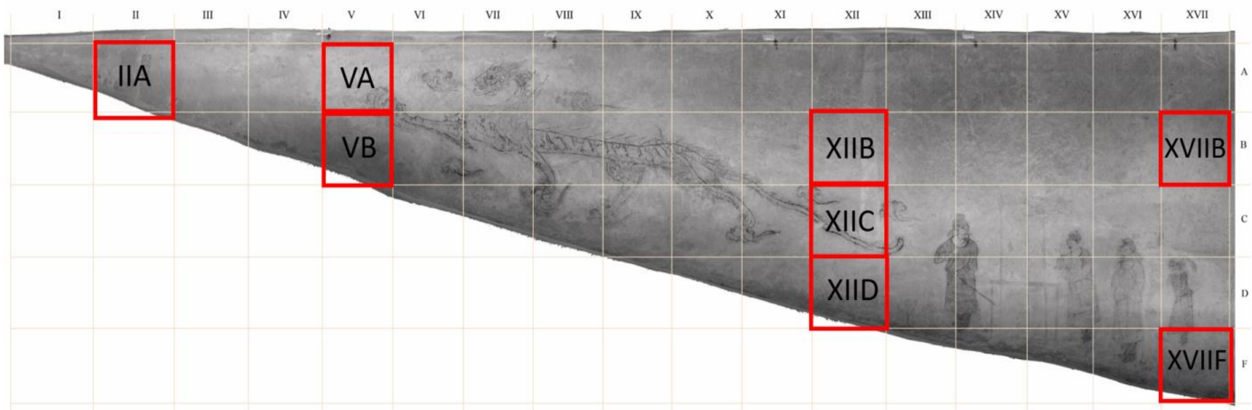

Figure 4.12. Observation points for salt precipitation on the western wall of the open dromos

Table 4.2. Observation results of the amount of salt precipitation on the surface of the western wall. Mark: (-) not detected, (+) Trace, (++) Minor constituent, (+++) High constituent, (++++) Major constituent.

	Sep	**Nov**	**Jan**	**April**	**May**	**June**
IIA	-	++	++	++	++	+
VA	+	++	++	+	+	+
VB	++	++++	++++	+++	++++	++++
XIIB	+	++++	+++	+++	++	+
XIIC	-	++	+++	++	+	+
XIID	-	+	++	+	+	-
XVIIB	+	+	++	+		+
XVIID	-	+	+	-		-

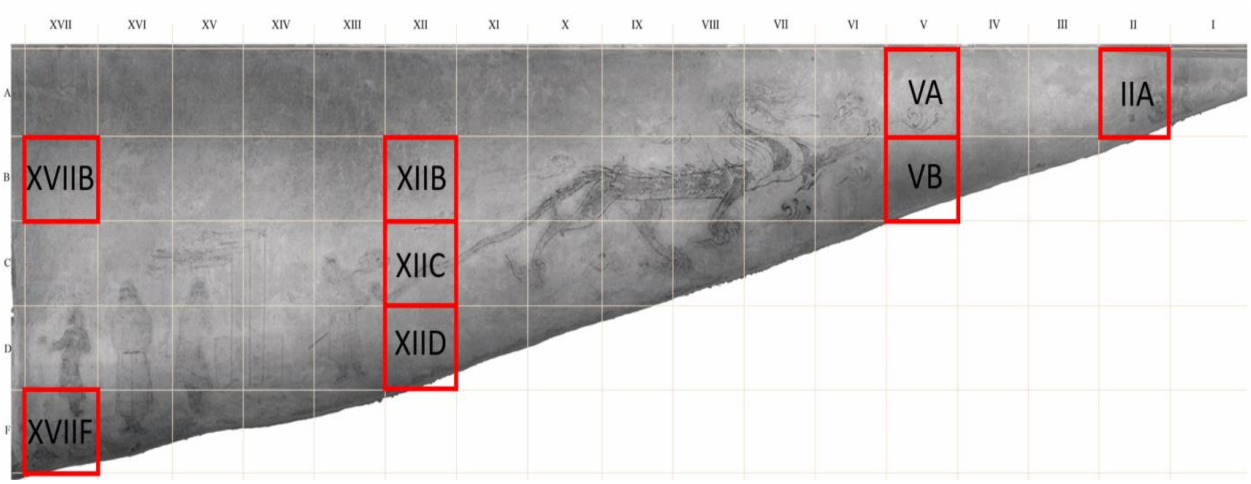

Figure 4.13. Observation points for salt precipitation on the eastern wall of the open dromos

Table 4.3. Observation results of the amount of salt precipitation on the surface of the eastern wall. Mark: (-) not detected, (+) Trace, (++) Minor constituent, (+++) High constituent, (++++) Major constituent.

	Sep	Nov	Jan	April	May	June
IIA	+	++++	+++	+++	+++	++
VA	-	++++	+++	+++	+	+
VB	-	++++	++++	+++	+++	+
XIIB	+	+	+	+	+	+
XIIC	-	-	+	-	-	-
XIID	-	+	+	+	+	-
XVIIB		-	-	+	+	+
XVIID	-	-	-	-		-

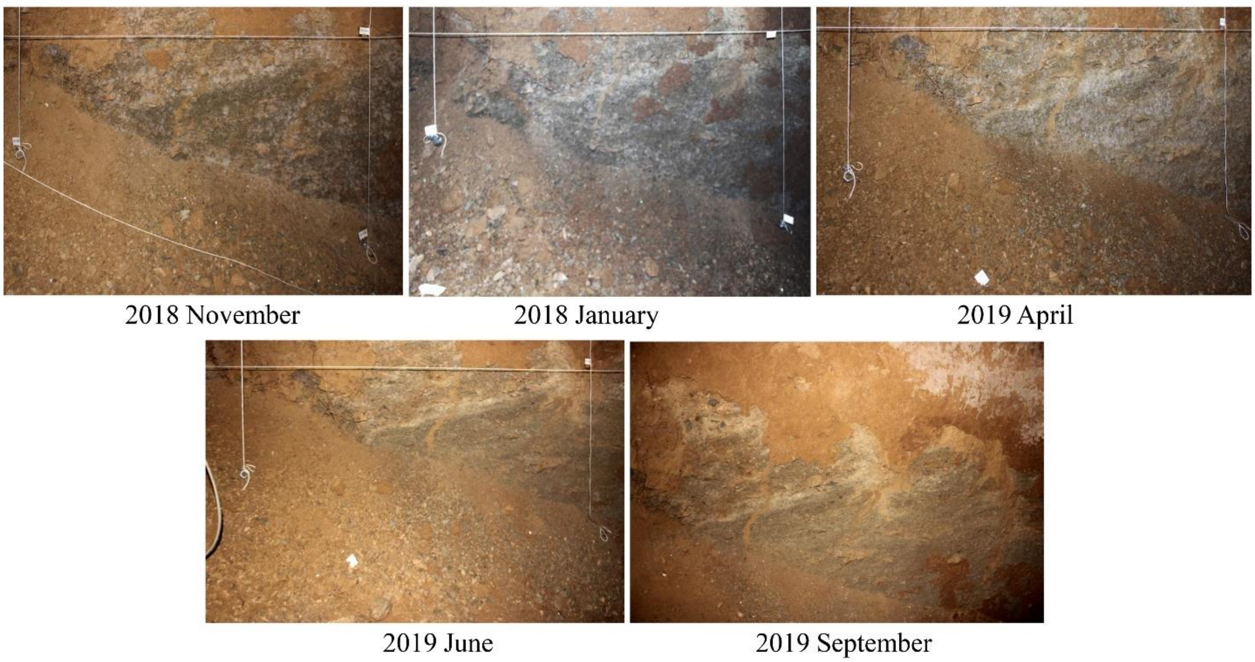

Figure 4.14. Salt crystallization phenomenon on the surface of the western wall, open dromos from November 2018 to September 2019. (Observation point VB)

4.7 Summary

The factors responsible for the deterioration of the Shoroon Bumbagar tomb are presented. The deterioration observed by visual observation at the burial chamber, airshafts, and open dromos, which is the subject of this study, includes:

1) condensation, lack of cohesion of the bedrock, and fungal growth on the mural paintings and wooden supports in the airshafts and burial chamber, and 2) detachment and peeling of the preparatory layers on the wall surfaces and upper parts of the airshafts. In addition, the precipitated salt on the mural surface was identified as thenardite by XRD analysis. This salt crystallized in both walls of the open dromos during the beginning of winter and spring. Thenardite significantly

deteriorates the porous materials, and seasonal variations in the hydrothermal environment in the tomb and outside weather may induce periodic crystallization cycles including moisture evaporation, dew condensation on the surface, and changes in the relative humidity and temperature.

The deterioration area distribution of the mural paintings of the Shoroon Bumbagar tomb increased with time. Therefore, a more detailed observation survey was conducted in each season. The monitoring and documentation of the deterioration area of the open dromos showed that the most active deterioration zone of the mural were the middle parts of the western and eastern walls. This process mainly occurred at a depth of two meters below the ground level.

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Chapter 5. Preservation of the Shoroon Bumbagar tomb based on the environmental survey

5.1 Introduction

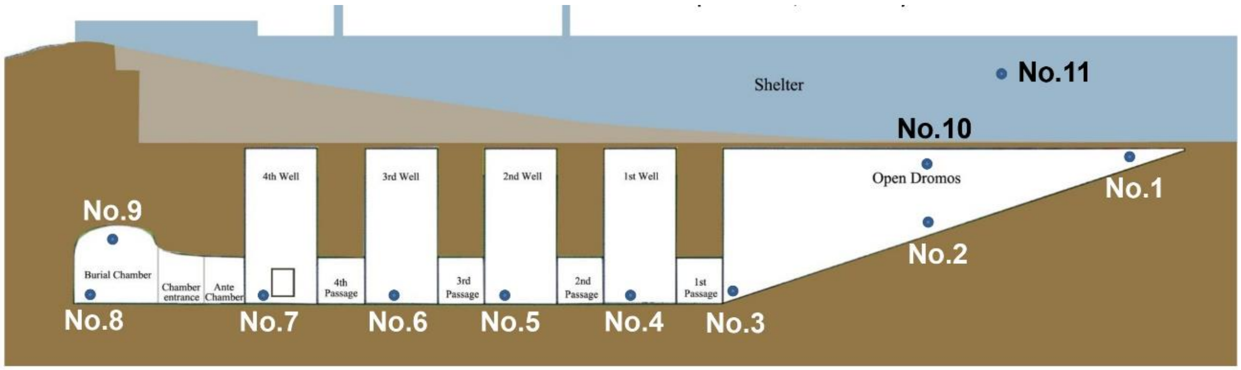
Although many conservation and preservation activities have been carried out after the discovery of mural paintings, no environmental survey or internal climate examination of the tomb has been conducted. This chapter describes the effect of the surrounding environment on the microclimate within the shelter, burial chamber, airshafts, and open dromos. In addition, changes induced in the internal environment due to external environment were assessed by keeping the open dromos closed during the cold season and reopening it during the warm season.

5.2 Methodology

The purpose of the first investigation survey was to examine the microclimate to determine the environmental factors that affected the preservation conditions of mural paintings during 2017 and 2018. The environment survey was performed within the tomb. Onset thermo-hygro sensors were used to measure the air temperature and relative humidity within the open dromos, wells, burial chamber, and temporary shelter used during the investigation survey. In addition, the temperature and relative humidity were measured outside the tomb since March 17, 2017. The Locations of measurements are shown in Table 5.1 and Figure 5.1. Temperature and relative humidity have been measured at intervals of fifteen minutes by using a data logger HOBO pro v2 U23-001, manufactured by Onset Computer Co., Ltd., with an accuracy of ±0.21°C and ±2.5% from 10 % to 90% RH, resolution of 0.02°C, 0.05% and operation range -40°C to 70°C. (www.onsetcomp.com).

Table 5.1. Information of installed measurements

Measurements No.	Installed location	Installed height above floor
No.1	Open dromos	30 cm
No.2, No.3,	Lower part (open dromos)	30 cm
No.4, No.5, No.6, No.7	Lower part (airshaft)	30 cm
No.8	Lower part (Burial chamber)	30 cm
No.9	Upper part (burial chamber)	150 cm
No.10	Upper part (open entrance)	160 cm
No.11	Ceiling (shelter)	160 cm



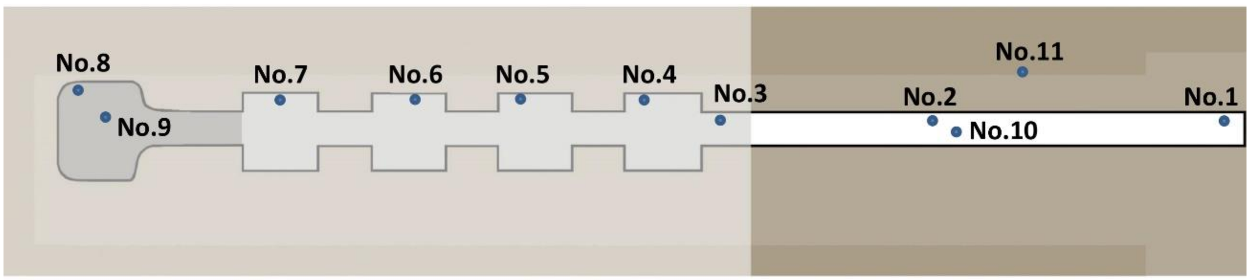


Figure 5.1. Appearance of the tomb and installed measurement location

5.3 Results and discussion

5.3.1 Survey of thermal environment inside the airshafts and burial chamber

Till date, the information on the internal conditions and environmental changes due to variation in the seasonal temperature during warm and cold weather seasons is limited because studies to determine the environmental effect on the Shoroon Bumbagar tomb have not been conducted. Considering the deterioration observed in the tomb (described in Chapter 4), the high humidity inside the tomb is a favorable environment for fungal growth. Furthermore, the instability in temperature and humidity causes salt precipitation. In other words, moisture evaporation from the wall surface creates conditions for the accumulation and further crystallization of salt on the surfaces of the mural paintings. In particular, the major deterioration is confirmed by the precipitation of sodium sulfate salt (mirabilite) in open dromos, which is known to severely deteriorate the porous materials. Therefore, to prevent deterioration due to salt precipitation, the internal conditions in the tomb and the environmental effects need to be determined by monitoring the temperature and humidity levels, particularly in cold weather seasons.

5.3.1.1 Winter and spring

Figures 5.2 and 5.3 show the changes in the daily average values of temperature, absolute humidity, and relative humidity inside the airshafts and the burial chamber throughout the year.

According to the hydrothermal measurements during 2017, the temperature in the shelter changed according to the outside air temperature during winter and spring. The outside air temperature varied from -40 °C to 36 °C, with an annual average of 1.7 °C. In these seasons, the air temperature in the airshafts and burial chamber fluctuated lesser than the air temperature outside and inside the shelter. In winter, the lower part of the fourth airshaft was the coolest with a temperature between 0 °C and -7 °C, while the burial chamber was the warmest during this period (Figure 5.3). The absolute humidity in the airshafts and the lower part of the burial chamber was similar during winter and spring. The absolute humidity of the airshaft fluctuated slightly owing to the air exchange through the gaps of the insulation foam board placed on the airshafts (Figures 5.4 and 5.5). The sealing method used in this year was not effective. The relative humidity of the shelter was almost saturated during winter and spring. The relative humidity in the airshafts and lower part of the burial chamber decreased significantly during this period. In addition, the relative humidity in the upper part of the burial chamber was at a saturated level (Figure 5.5).

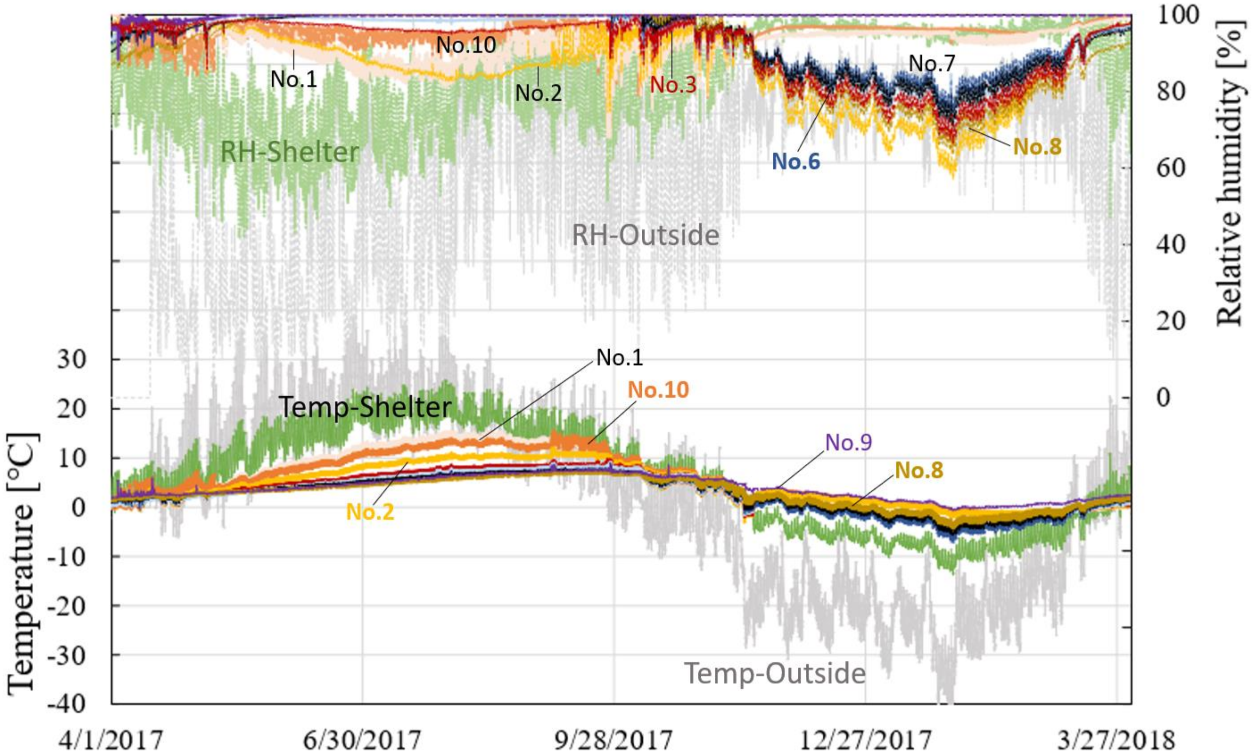


Figure 5.2. Air temperature and relative humidity in the burial chamber, airshafts and open dromos whole year (April 1, 2017–March 27, 2018)

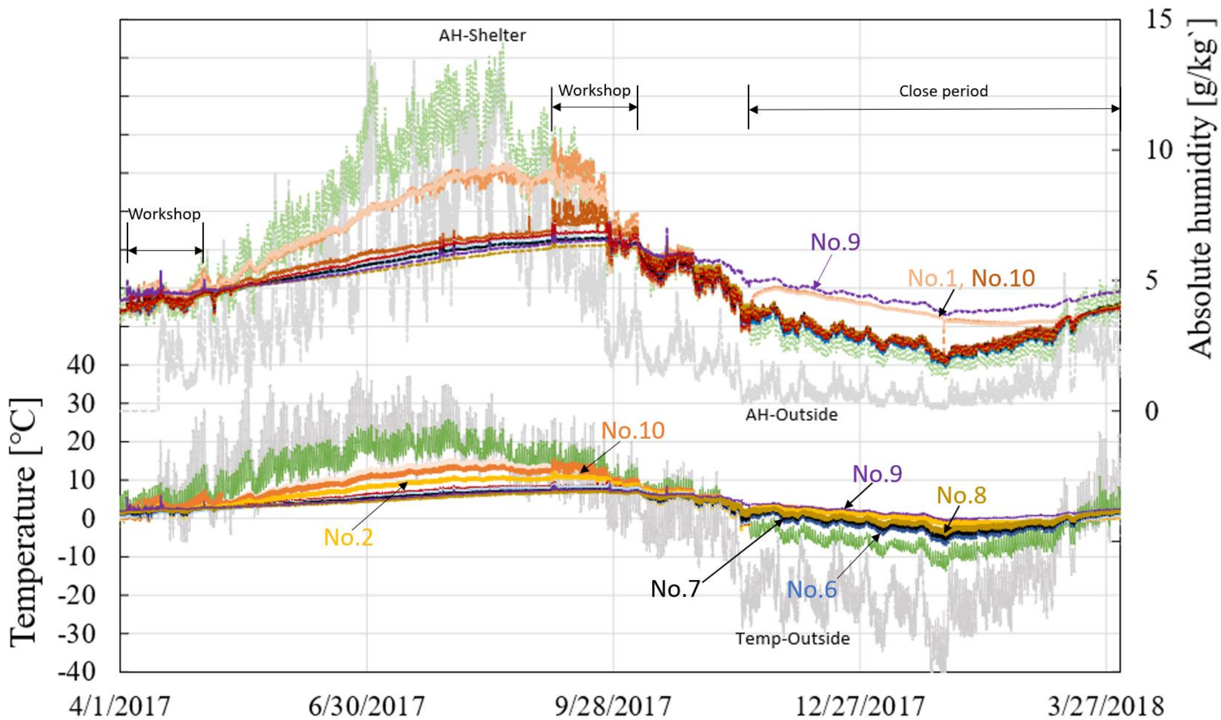


Figure 5.3. Air temperature and absolute humidity in the burial chamber, airshafts and open dromos whole year (April 1, 2017–March 27, 2018)

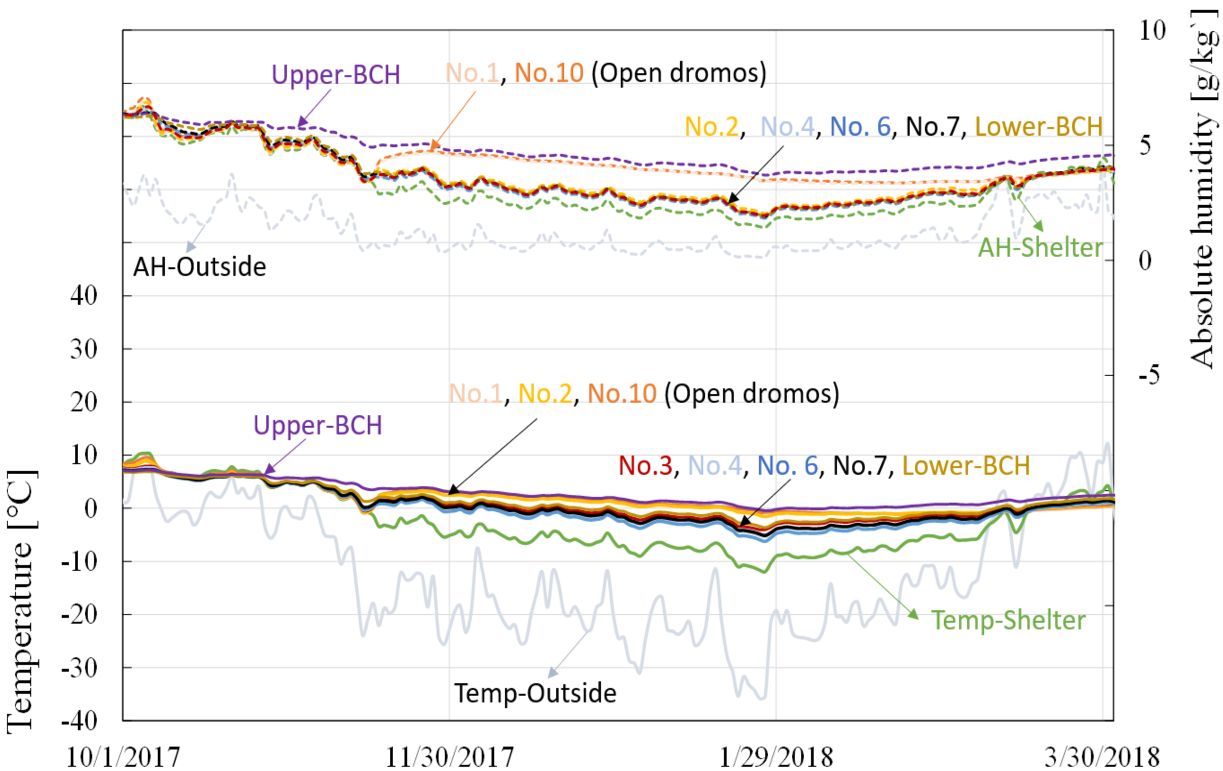


Figure 5.4. Air temperature and absolute humidity in the burial chamber, airshafts and open dromos during winter and spring (October 1, 2017–March 30, 2018)

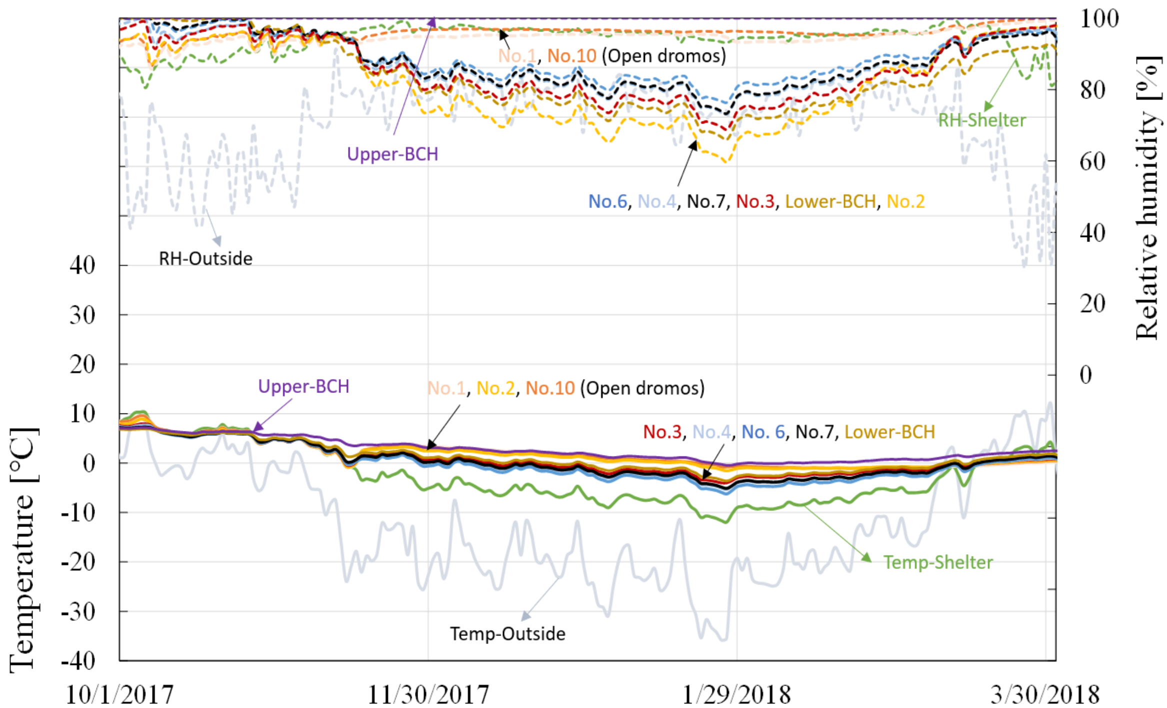


Figure 5.5. Air temperature and relative humidity in the burial chamber, airshafts and open dromos during winter and spring (October 1, 2017–March 30, 2018)

5.3.1.2 Summer

Figures 5.6 and 5.7 show the changes in the daily average values of temperature, absolute humidity, and relative humidity inside the airshafts and burial chamber, respectively. The temperature in the shelter changed according to the outside air temperature during summer. The air temperature in the airshafts and burial chamber was stable. The absolute humidity in the shelter was higher than that outside during summer. During this period, the relative humidity in the shelter, airshafts, and burial chamber was 100% (Figure 5.7).

5.3.1.3 Autumn

The temperature in the shelter, airshafts, and burial chamber changed with variation in the outside temperature in autumn. In addition, their absolute humidity levels changed in the same manner as that of the shelter air during autumn. Air ventilation was observed in the shelter. During this period, the relative humidity in the shelter, airshafts, and upper part of the burial chamber decreased slightly.

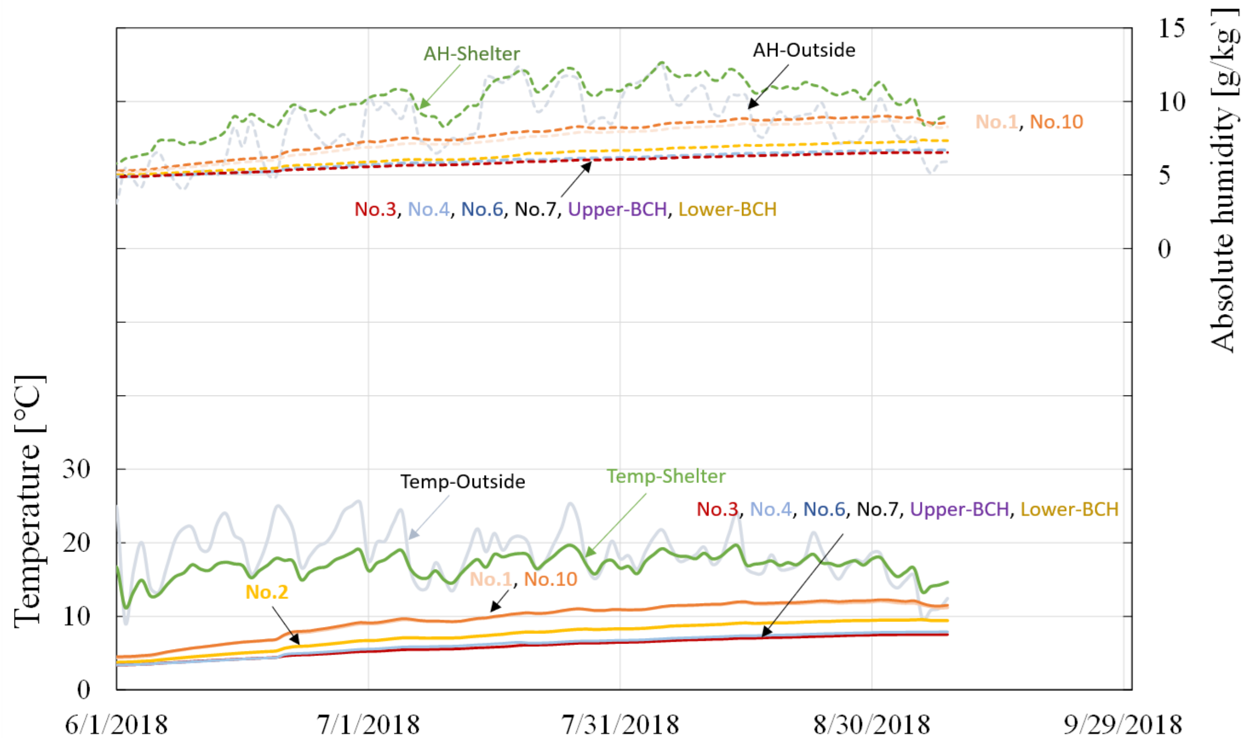


Figure 5.6. Air temperature and absolute humidity in the burial chamber, airshafts and open dromos during summer and autumn (June 1, 2018–September 30, 2018)

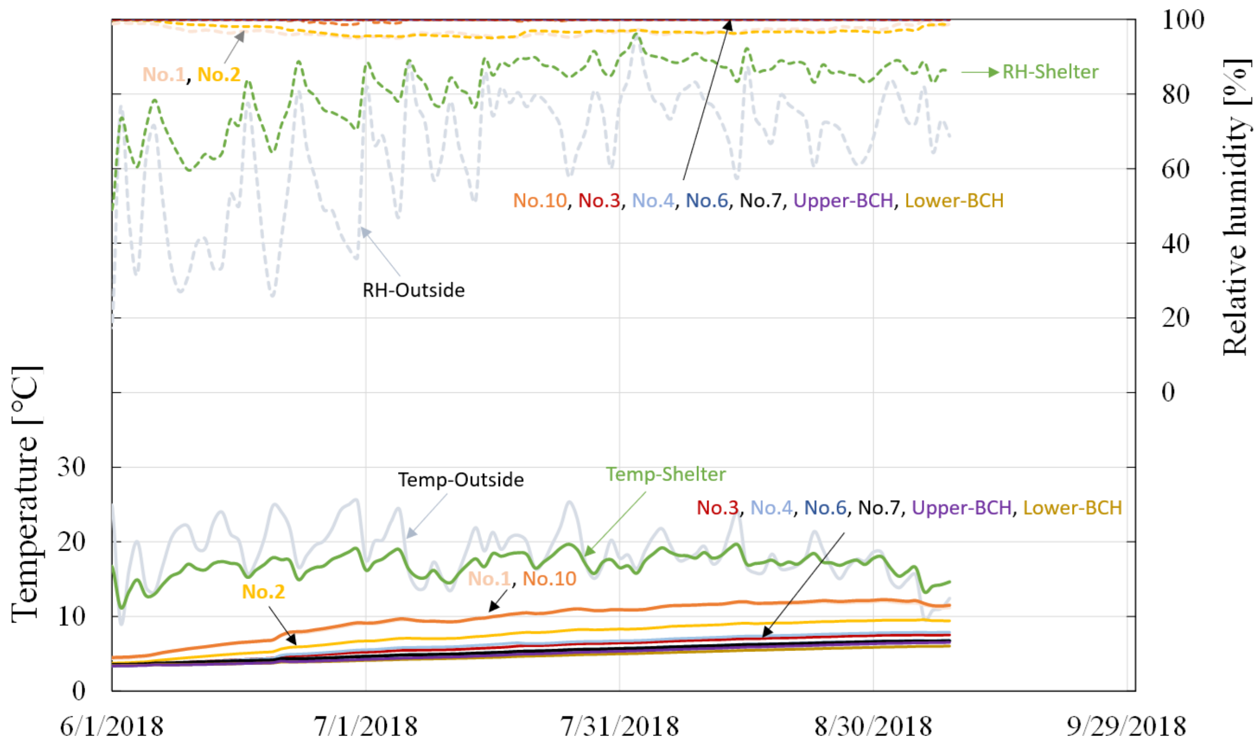


Figure 5.7. Air temperature and relative humidity in the burial chamber, airshafts and open dromos during summer and autumn (June 1, 2018–September 30, 2018)

Hydrothermal results for the four seasons indicated that heat transfer was different inside the tomb. In summer, heat flow into the burial chamber from the open dromos and airshafts was observed, while in winter, heat flow out of the burial chamber was noted. Therefore, the warmest place in winter and the coldest place in summer was inside the burial chamber. In the cold season, the internal conditions of the airshafts and the lower part of the burial chamber were affected by air ventilation from the gaps around the covering material on the top of the airshafts. Thus, ventilation led to a decrease in the relative humidity of the airshafts during this period. Thus, moisture could evaporate from the walls. During this time, soluble salt efflorescence could crystalize in the vicinity of the surface layers of the mural paintings after water evaporation due to ventilation. Therefore, it was necessary to suppress the ventilation frequency during winter and spring.

5.3.2 Thermal environment inside the open dromos

Based on the results of the observation survey, temperature and relative humidity inside and outside the shelter significantly affected the deterioration of the mural paintings. A metallic shelter was constructed over the tomb to protect it from wind, rain, and snow. The heat conductivity of the metallic shelter was high. In the cold season, the internal temperature of the shelter was higher than the outside temperature. Additionally, the internal temperature of the shelter was higher than the outside temperature in summer. In summer, the evaporation rate of water from the walls of the tomb increased with an increase in the internal temperature of the shelter. During this season, the relative humidity was very high. During the cold season, the walls and ceiling of the shelter were completely covered with frost.

Since 2012, the National Center for Cultural Heritage closes the open dromos and airshafts of the Shoroon Bumbagar tomb in November and reopens these between May and June (Table 5.2). The open dromos was covered with an insulating foam, a blanket, and a polythene sheet, while the top of the airshafts was covered with only the insulating foam (Figure 5.8.a).

Table 5.2. Open and closing period and sealing method for the open dromos

Year	**Close period**	**Open period**
2012	November	June
2013	November	June
2014	November	May
2015	November	May
2016	November	May
2017	November	April
2018	November	June

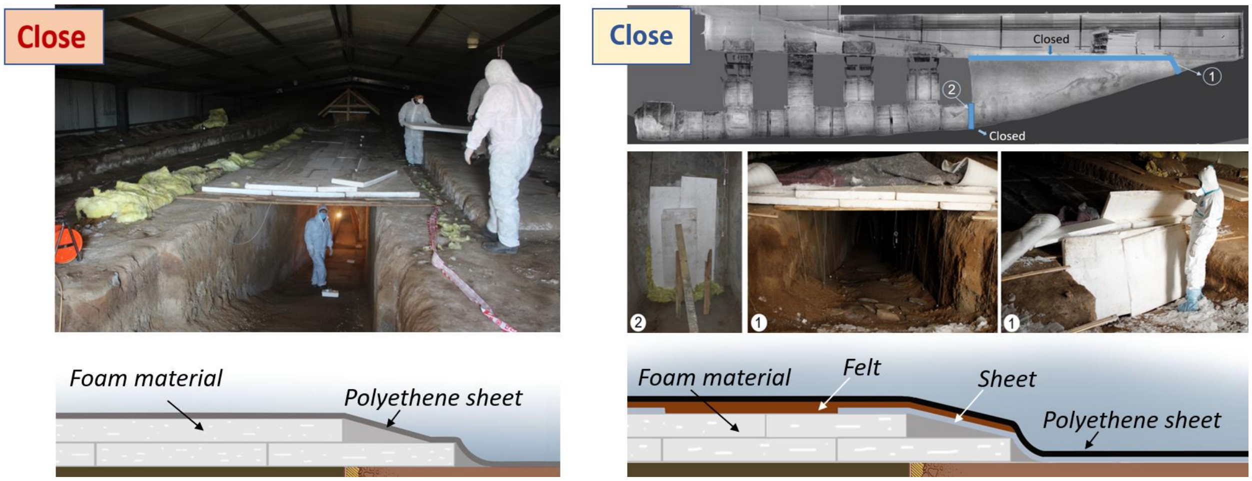


Figure 5.8. Open dromos condition during open and close period. a) Before sealing method, b) After improving the sealing method (1) and closed the first corridor (2)

5.3.3 Examination of the thermal environmental survey results after closed and open intervention

Figure 5.9 shows the changes in the daily average values of temperature, absolute humidity, and relative humidity inside the open dromos during the open and closed periods.

The major deterioration of the mural paintings of the open dromos constituted salt weathering on the wall surface. This type of salt crystallization particularly occurred from November to June each year. The solubility of salt crystals depended on the correlation between the temperature and relative humidity of the open dromos. Some studies reported that the degradation of the cultural heritage due to salt accumulation could be suppressed by controlling the microclimate of the shelter (Wakiya et al., 2019; Keshi et al., 2015; Kiriyama, 2017; Takatori, 2017; Wakiya & Kohdzuma, 2017). From this standpoint, preservation intervention of the Shoroon Bumbagar tomb was implemented to decrease the ventilation frequency during the cold season from 2017 to 2020. Sections No. 1, No. 2, and No. 10 (open dromos) were warmer than other parts in the cold season. In addition, the temperatures in these parts showed minor fluctuations. When the open dromos was closed in winter and spring, the absolute humidity of No. 1 and No. 10 suddenly increased. During this period, the inside of the open dromos was very humid, that is, the relative humidity was almost 100%. The absolute humidity of the lower part (No. 2) was lower than that of the upper part when the open dromos was closed. The air was ventilated through the first airshaft (Figure 5.10). The next year, the passing corridor of the open dromos was sealed (Figure 5.8.b), and as a result, the absolute humidity in the lower part (No. 2) of the open dromos reached the same level as in the upper part (No. 1 and No. 2) of the open dromos. Despite the above intervention, there was less suppression of salt crystallization on the mural surface, and the mural paintings continued to collapse. Figure 5.12 shows the salt crystallization on the western wall of the open dromos in November 2017 and November 2020.

In summer, the ground was colder than the shelter, and the opposite was observed in winter. Natural ventilation through the open entrance afforded less fluctuations during the warm season.

The temperature of the shelter varied according to the outside temperature, but the daily temperature fluctuation was smaller than the outside temperature. The upper and lower parts of the open dromos (No. 1, No. 2, and No. 10) were warmer than the lower part of the airshaft (Figure 5.7). The absolute humidity of the shelter was higher than that of the outside. During this period, the absolute humidity of the upper parts of the open dromos (No. 1 and No. 10) changed according to the absolute humidity in the shelter. The inside of the open dromos was very humid, that is, the relative humidity was almost 100% (No. 1, No. 2, No. 10, and No. 3).

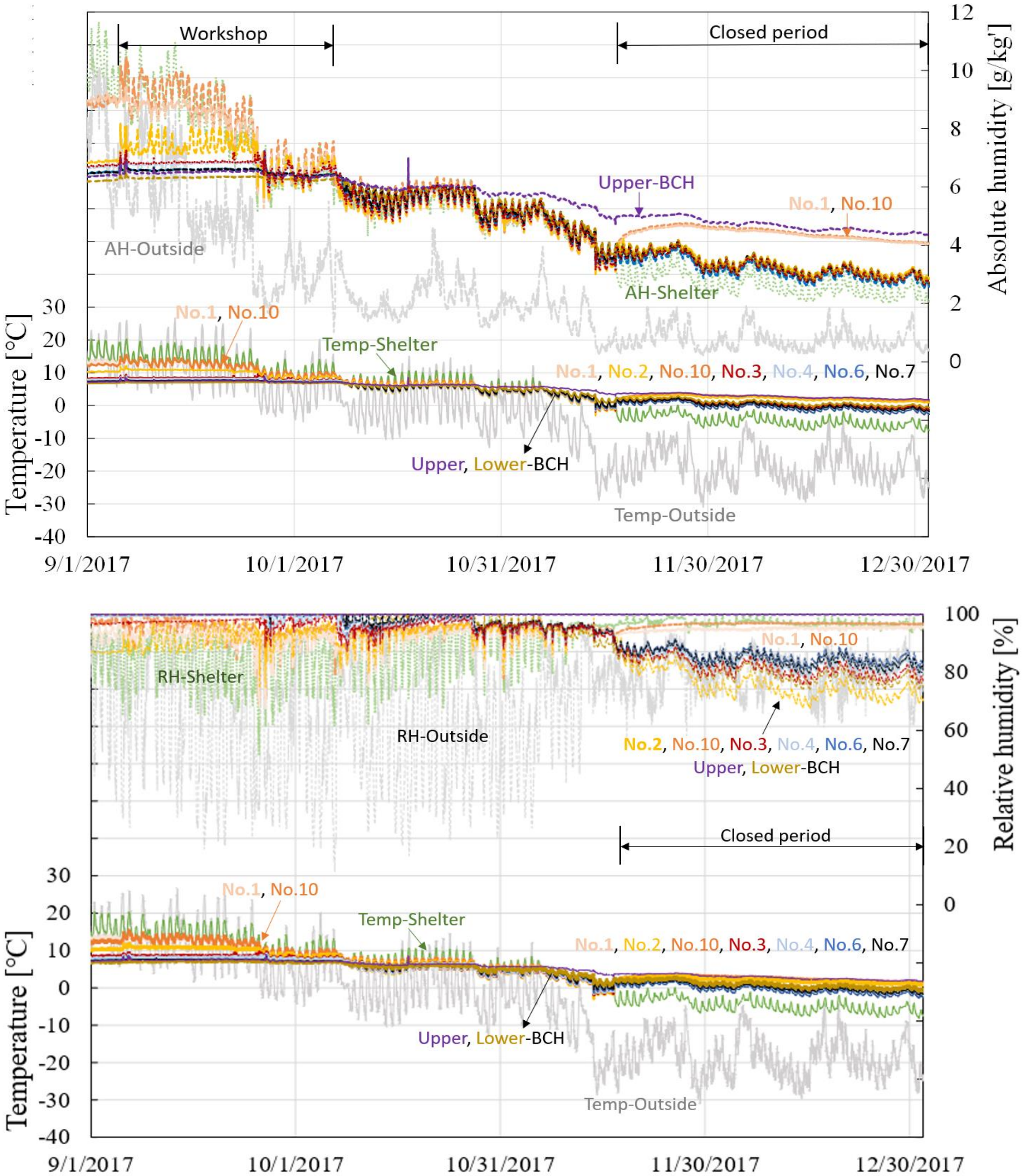


Figure 5.9. Air temperature, absolute humidity and relative humidity in the burial chamber, airshafts and open dromos (September 1, 2017–December 30, 2017)

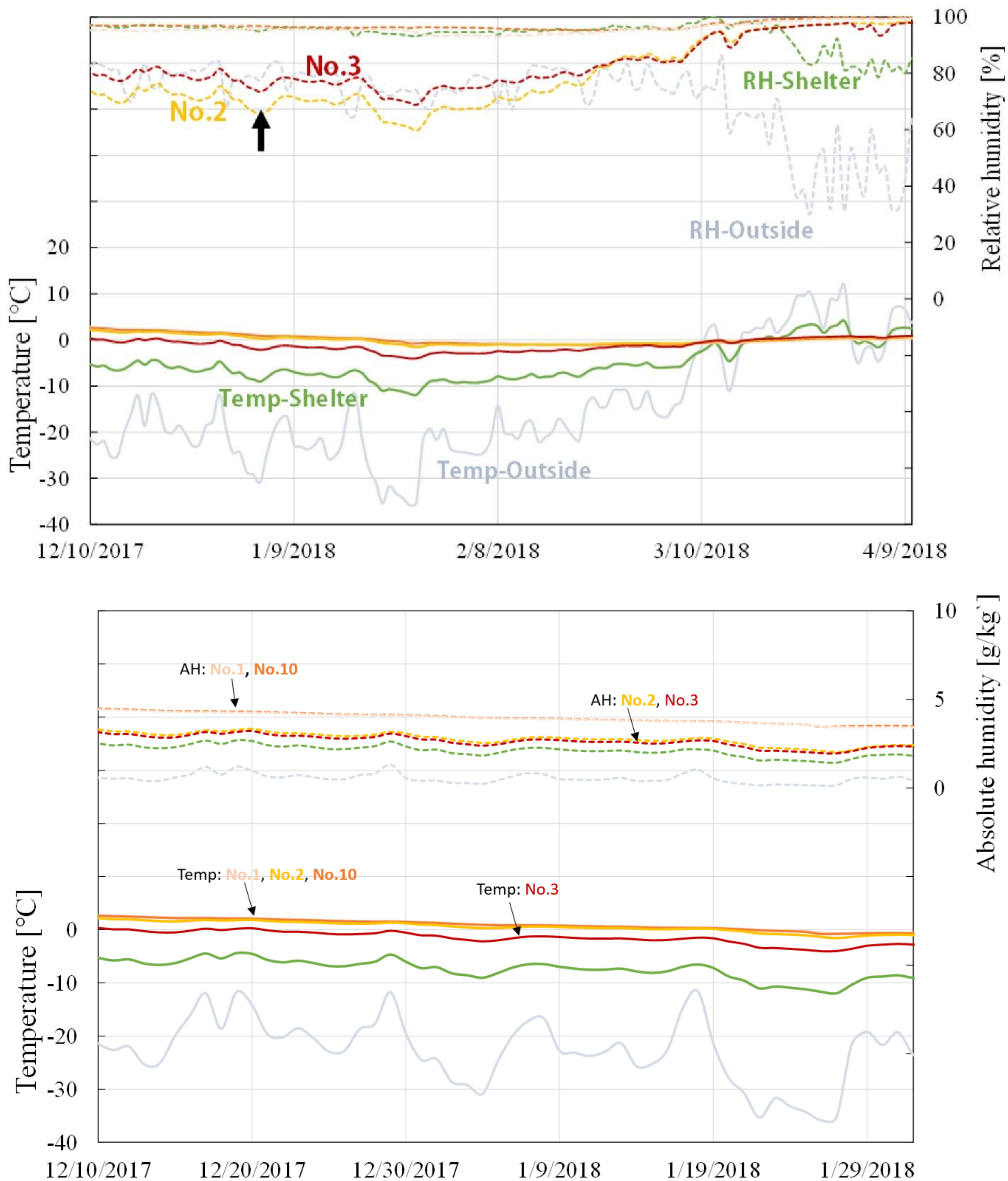


Figure 5.10. Temperature and absolute humidity in the open dromos before sealed the passing corridor

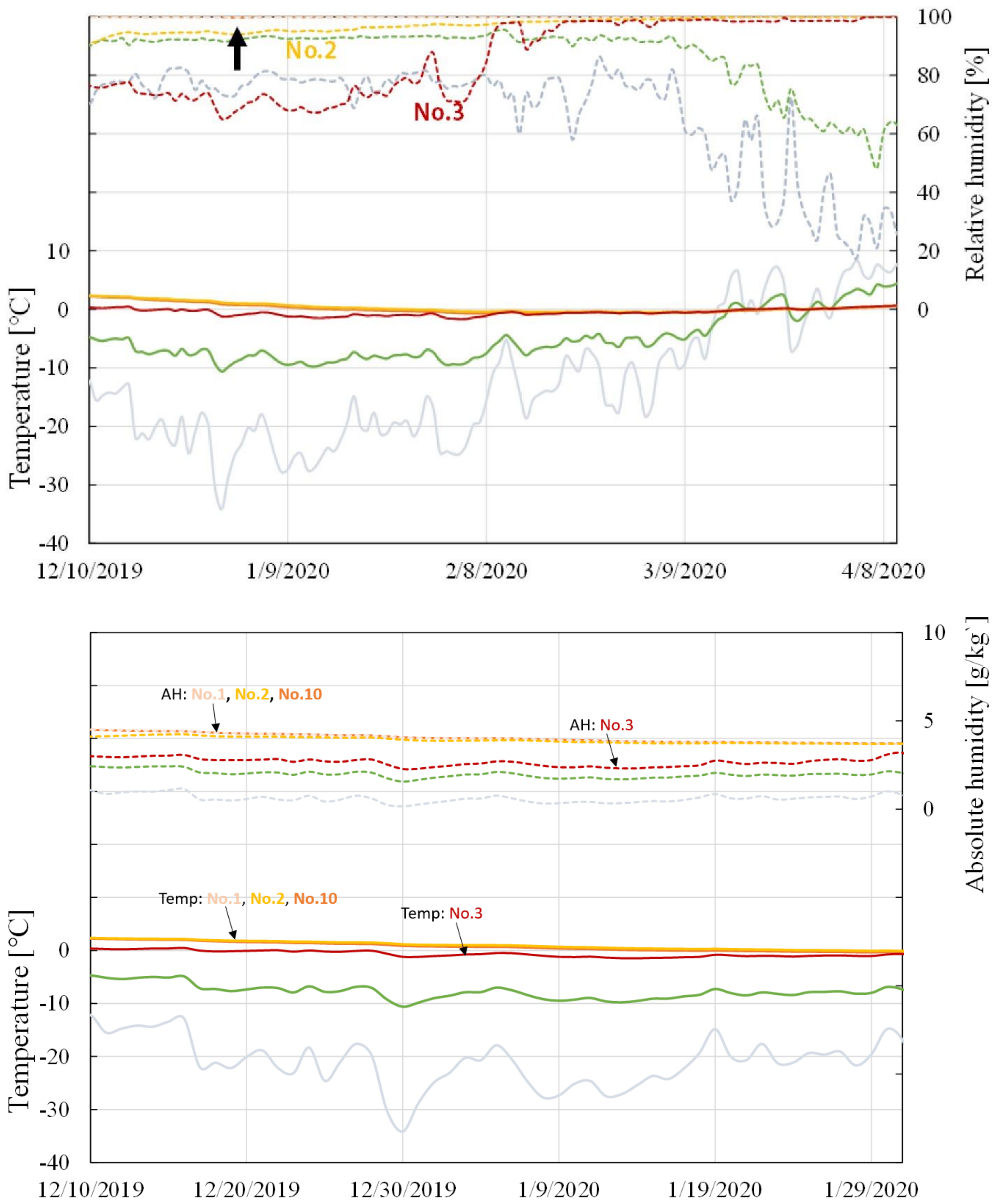
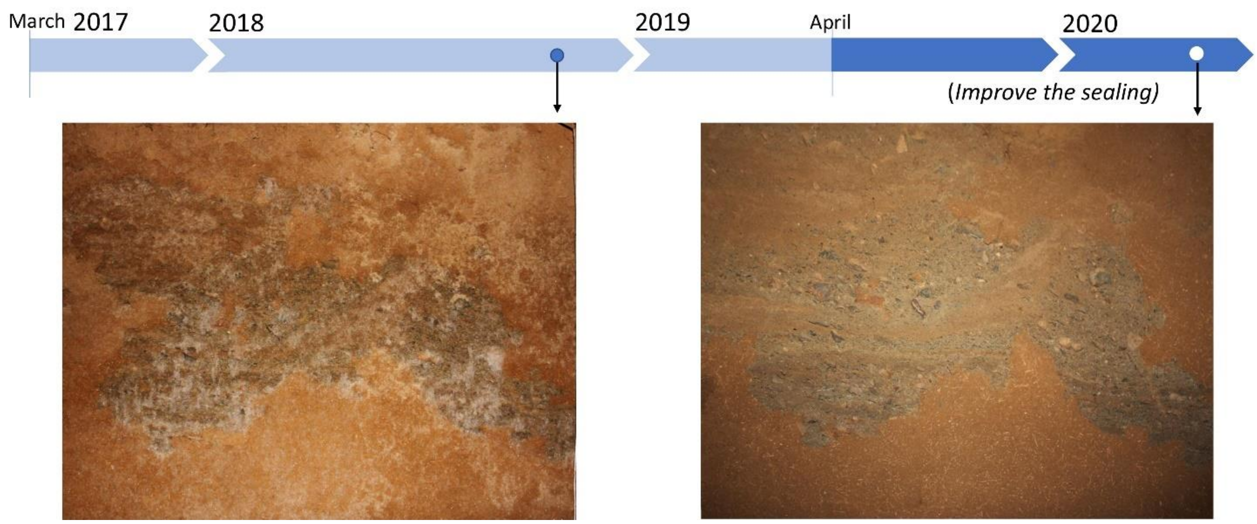


Figure 5.11. Temperature and absolute humidity in the open dromos after sealed the passing corridor



November 2018 November 2020

Figure 5.12. Salt crystallization condition on the western wall of the open dromos

5.4 Summary

The aim of this study was to determine the effect of hydrothermal environmental conditions inside the airshafts and burial chamber of the Shoroon Bumbagar tomb with seasonal changes, as well as examine the effect of the surrounding environment on the internal environment of the open dromos that could subsequently allow the establishment of the relationship between the environmental conditions and deterioration of the mural paintings. The Shoroon Bumbagar tomb was designated as a national historical site in Mongolia in 2020. In this study, an on-site environmental survey was constructed for several years. Based on the results of the survey, the following conclusions were reached.

The relative humidity in the upper part of the burial chamber remained constant (almost 100%), and the walls of this area were constantly wet due to condensation. When the surface of the wall was saturated with moisture, it provided favorable conditions for the growth of the mold.

When the top parts of the airshafts were closed during the cold season, outside air ventilation through the covering material was observed, which led to a decrease in the relative humidity of the airshafts. Consequently, soluble salt efflorescence could crystalize on the surfaces of the mural paintings. Therefore, it is necessary to suppress the ventilation frequency during the cold season.

In an open environment during summer, the relative humidity of the open dromos was almost 100%. Although the high humidity in the open dromos allowed low moisture evaporation from the walls, it could negatively affect the mural paintings by providing a favorable environment for the growth of mold and microorganisms.

Outside air ventilation was observed in September. Therefore, it is better to close the open dromos and airshafts from the beginning of September.

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Chapter 6. A case study: Environmental survey inside the Yokoana tombs

6.1 Introduction

The Miyazaki City Board of Education is planning to open some of the Yokoana tombs to the public as part of their activities. In such a situation, the relics should be preserved without causing damage or deterioration to the stone material as far as possible. Unfortunately, there were intractable problems, such as detachment and surface peeling of the stone materials of the tomb. It was therefore immediately to determine the characteristics of the microenvironment inside the tomb at the present time, and to track, how the deterioration of the relics is affected by the external environment. In order to minimize the risk of deterioration caused by opening the tombs up to visitors, this study is able to recommend which seasons the tomb could be safely opened or shown to the public and in which it should be closed. As the first step of our study, selected two Hasugaike Yokoana tombs (No.16 and No.17) with a similar shape and size, located in the hillside with a combination of sandstone and mudstone formations. It was possible to assess how the internal environment changes due to the external environment by keeping one tomb permanently closed and the other permanently open and comparing the two.

In addition, we have included results from a hydrothermal environmental survey conducted inside Yokoana tombs No.16 and No.17. The aim of this survey was to examine the influence of the surrounding environment on the internal environment of the tombs and determine the wetting and drying cycles in the tomb due to seasonal changes. Having examined these, I was able to propose better indoor environmental control methods in order to decrease the tombs' deterioration and to suggest a method for suppressing the impact of the same.

6.2 Outline of the investigation field

The site of the historic Hasugaike Yokoana group of cave tombs is located in Miyazaki city, Miyazaki prefecture, Japan (Figure 6.1). The hilly area in which the Yokoana group tombs are distributed is divided into three successive ponds: Hasukaike, Nakaike and Taike. In total, 82 Yokoana tombs were identified. The tombs were divided into seven groups: A, B, C, D, E, F, and G (Miyazaki City Board of Education, 1990).

The tombs were made from the second half of the sixth century to the beginning of the seventh century. Some tombs have been destroyed and opened due to natural disasters, and some have been excavated when a village road was being created, trees were being planted, and so on, but most have been looted. Each Yokoana tombs is of a different size. Some tombs have engravings that are executed on uneven walls (Miyazaki City Board of Education, 1990).

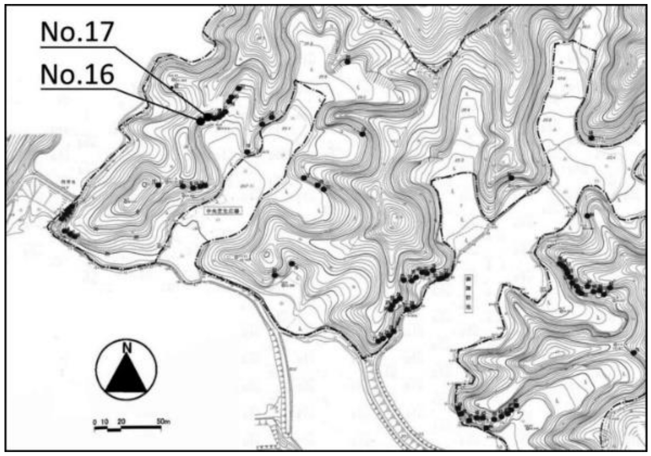


Figure 6.1. Location of the historic site Hasugaike Yokoanagun group tombs with the position of tombs No.16 and No.17 marked. (© Miyazaki City Board of Education, 2012)

The plans for land development were processed, and an emergency excavation was conducted by the Prefectural Board of Education in 1965. Based on the results of this emergency excavation survey, this site was designated a national historic site in Japan in 1971 (Miyazaki City Board of Education, 1992). In 1984, the preservation project of the historical site Hasugaike Yokoanagun began. The following year, the basic concept and design of the site management plan were established (Miyazaki City Board of Education, 1993). The first step in the preservation work was to restore the collapsed entrance. Blockade stones were stacked to avoid fluctuation in the temperature and humidity inside the chamber. The construction for the preservation work of the Hasugaike Yokoana group tombs took place over seven years, from 1986 to 1993 (Miyazaki City Board of Education, 1993). In 1995 and 2000, restoration work, such as repairing the exposed and collapsed areas of the entrance as well as the surface of the burial chamber, were performed. From 2010 to 2012, an examination survey of indoor conditions inside 24 tombs that had been opened was conducted (Miyazaki City Board of Education, 2012).

Yokoana tombs No.16 and No.17 were discovered in 1987 (Figure 6.2), and as part of their preservation project, construction work was performed to rebuild their collapsed front walls. Conservation treatment was carried out as follows: first, the surface of a wall that was subjected to progressive decomposition due to natural factors was consolidated in position; second, FRP with glass fiber was applied to the wall; third, a flat framework of stainless-steel round bars was assembled; fourth, polyurethane foam was sprayed on the stainless-steel net; fifth, FRP mixed with glass fiber was used to cover the polyurethane foam; finally, it was polished with resin mortar mixed with soil (Miyazaki City Board of Education,1990). Figures 6.2 b and 6.3 show Yokoana tombs No.16 and No.17 before conservation as well as the illustration of the construction method. After finishing this construction work, two tombs were closed until an environmental study was carried out by the Nara National Research Institute for Cultural Properties in 2017.

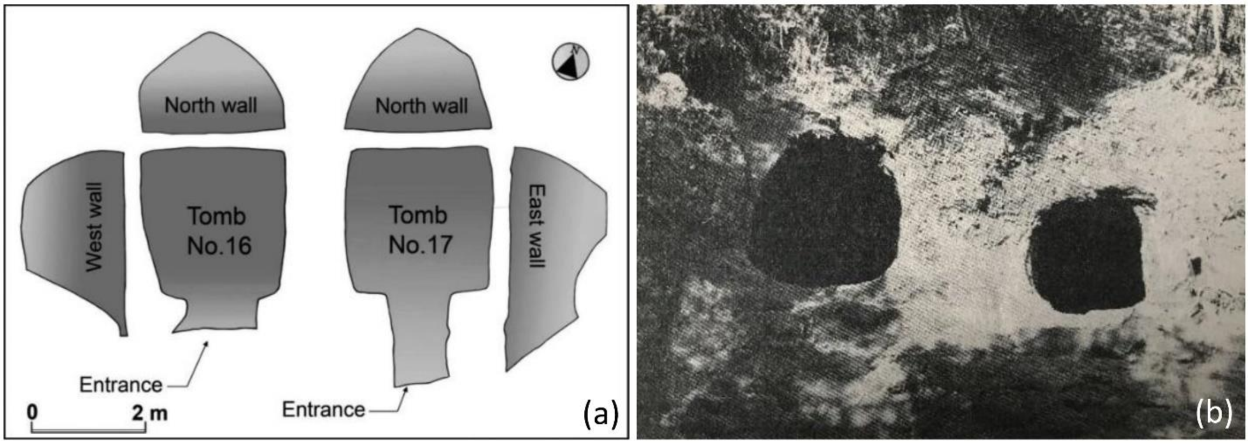


Figure 6.2. a) Location of the historic site Hasugaike Yokoana group tombs with the position of tombs No.16 and No.17 marked. b) Before construction work (Tombs No.16 and No.17), (© Miyazaki City Board of Education, 2012)

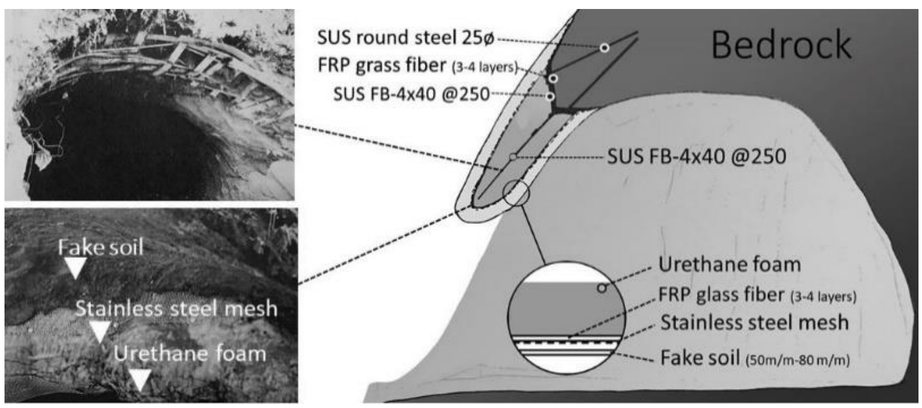


Figure 6.3. Construction method (Tomb No.16)

6.3 Deterioration of Yokoana tombs No.16 and No.17

That inside the tombs No.16 and No.17, it is possible to see how the people of that time had made the tomb and original surface of the wall. Currently the original appearance of the two tombs still needs to be conserved. Unfortunately, there were signs of white precipitation on the surface of the western wall and northern wall of the Yokoana tomb No.17 (Figure 6.4 a, b), plant root growth on the surface of the wall near the entrance (Figure 6.5 a, b and c), and a brown layer on the surface stone, which seems to originate from iron hydroxide precipitation (Figure 6.6). The bedrock is presumed to contain a large amount of iron. The surface of the walls suffered a lot of damage, and some parts of the original surface were lost. Detachment and surface peeling emerged as intractable issues (Figure 6.7).

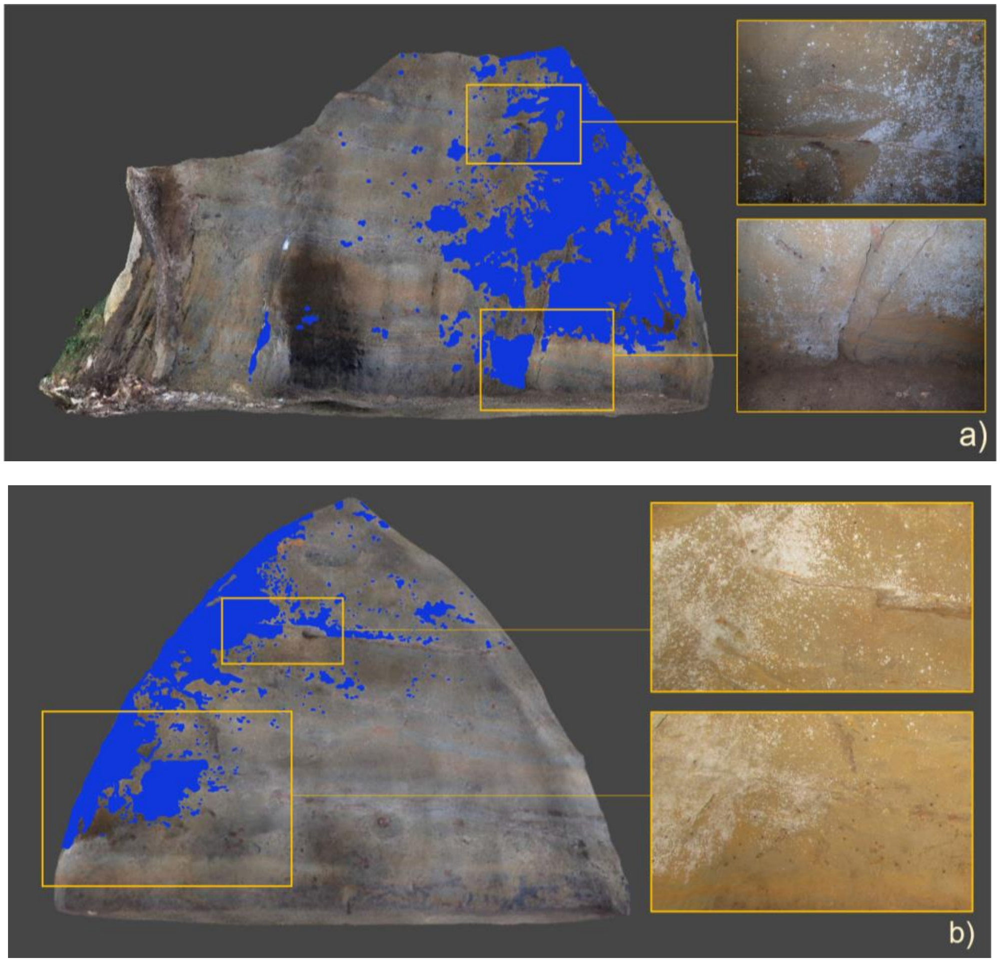


Figure 6.4. Deterioration of the Yokoana tomb No.17. a) White precipitation on the west wall. b) White precipitation on the north wall

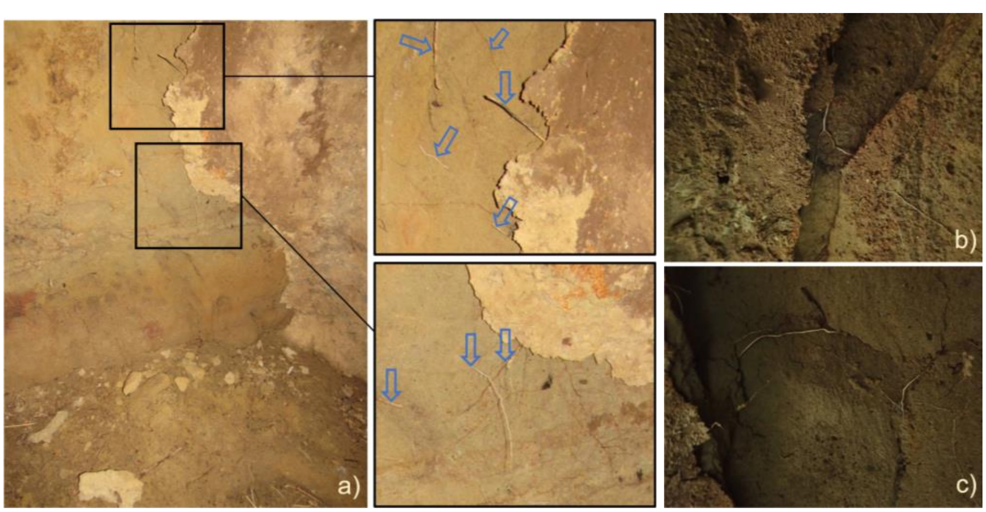


Figure 6.5. Deterioration of the Yokoana tomb No.16. a) Roots growing on the east wall near the entrance. b), c) Roots growing on the west wall near the entrance

Figure 6.6. Hydrated iron oxide precipitation on wall of the Yokoana tomb No.16

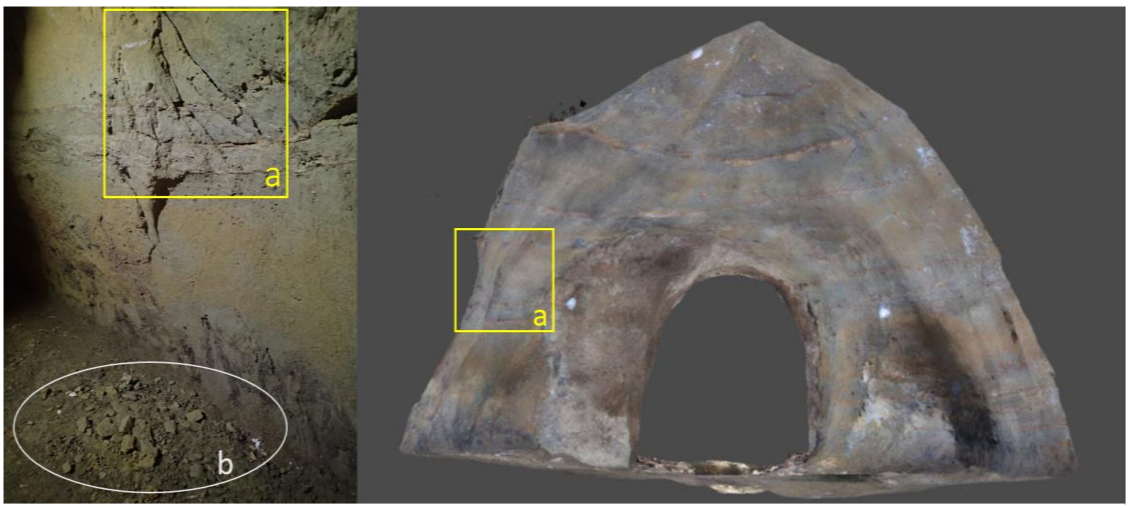


Figure 6.7. Deterioration of the Yokoana tomb No.17. a) Surface peeling of the wall near the entrance. b) State of falling under the sandstone detached from the wall

6.4. Investigation methods

6.4.1 Observation survey of the deterioration of stone materials

Observation surveys were conducted for each season (April, August 2017, May, August, November 2018, and April, October 2019). The aim was to determine whether dew condensation and salt precipitation occurred on the surface of the walls within the tombs owing to seasonal changes.

6.4.2 Temperature and relative humidity measurements

To evaluate the effects of creating a blockade for hydrothermal conditions on the preservation of the tombs, different conditions were set for tombs No.16 and 17: An entrance door was installed for tomb No.16, but not for No.17. Table 6.1 lists the tomb conditions.

Temperature and relative humidity were measured at a height above the floor level of 10 cm (lower part) and 150 cm (upper part) near the center of tombs since April 24, 2017 (Figure 6.8). The temperature and relative humidity were also measured outside the tomb. The measurements were conducted at intervals of 15 minutes using a data logger HOBO pro v2 U23-001, manufactured by Onset Computer Co. Ltd., with an accuracy of ±0.21°C and ±2.5% from 10 % to 90% RH and resolution of 0.02°C and 0.05%, respectively (www.onsetcomp.com).

Table 6.1. Information on condition and dimension of No.16 and No.17

	Entrance door	*Room width*	*Room depth*	*Ceiling height*
Tomb No.16	Open	2.0 m	2.6 m	1.8 m
Tomb No.17	Closed	2.4 m	2.6 m	1.8 m

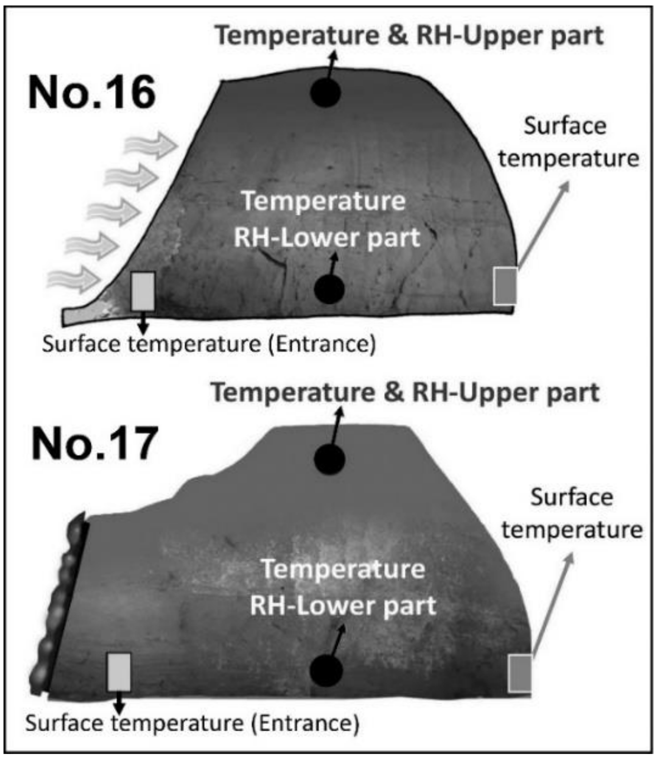


Figure 6.8. Appearance of the tombs and measurement location

6.4.3 Environmental survey of water distribution on the wall for dew condensation

6.4.3.1 Surface temperature measurement

The device for measuring surface temperature of inner wall was installed at a height above the floor level of 10 cm (lower part) on the north wall, near the entrance (Figure 6.8). Surface temperature measurements near the entrance were carried out since April 18, 2019, and surface temperature measurements at the lower part of the north wall were carried out since April 24, 2017 at a measuring interval of 15 minutes. The measurement device used was a data logger RTR-52A manufactured by the T&D Corporation.

6.4.3.2 Surface moisture measurement

The moisture on the surface of the tomb walls (No.16 and No.17) was measured using a portable handheld NIR moisture meter (JT-100, Kett Electric Laboratory). The on-site measurement was carried out four times between 2018 and 2019. The numerical values of the coefficient of IR (Infrared ray) absorbance on the stone surface were respectively marked as follows infrared absorbance code (IRAC):

- Triangle circle: 0.400-0.500
- White circle: 0.501-0.600
- Blue circle: 0.601-0.700
- Black circle: 0.701-0.800
- Red circle: 0.801-0.900

This study obtains the correlation between the coefficient of IR absorbance and the moisture content of a sandstone sample. Specimens were prepared with stone fragments that had collapsed around the Hasugaike Yokoana tomb. Specimens shaped into a rectangular parallelepiped of 1 cm × 2 cm × 2 cm were dried at 105°C for 24 hours. After the sandstone specimens had completely dried, they were placed in desiccators, which were provided with a constant humidity from 33% to 94% RH at 20 °C. After the specimens reached a given equilibrium state, the IR absorbance of each specimen was measured. On the other hand, the IR absorbance of water-saturated sandstone was measured after saturation with water under vacuum conditions.

6.5. Results and discussion

6.5.1 Observation survey of the deterioration of stone materials

According to the results of the observation survey of the deterioration in the tomb, the most severe detachment and peeling of the surface was observed in the ceiling and on the sides of the right and left walls near the entrance of both tombs (Figure 6.9). The north wall was less affected. The surface of the walls in both tombs did not wet as much in the winters as it did during the summers. No white precipitate was observed on the sidewalls of tomb No.16 throughout the year. However, prior to the environmental survey, white precipitate had spread across the wall surface of tomb No.17. The results of the observation survey indicated no increase in the white precipitate on the wall. Samples of the same were taken and investigated using the XRD analysis. No salt was detected in any of the samples.

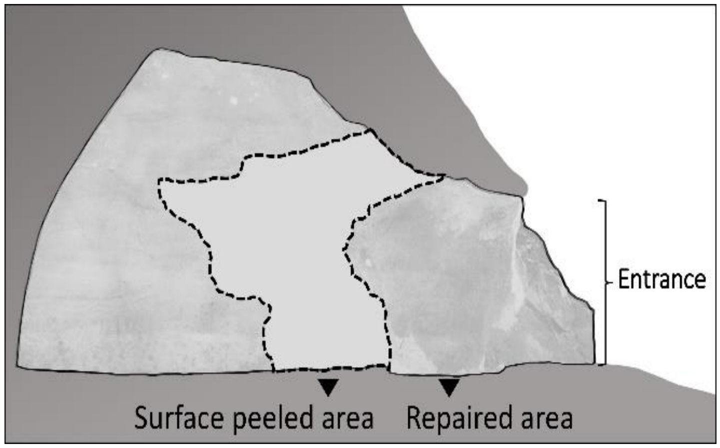


Figure 6.9. Deterioration condition of the eastern wall of the Yokoana tomb No.17. The marked line indicates area of loss and surface peeling on the wall

6.5.2 Deterioration factors affecting stone material

Under the conservation and environmental survey project of the Hasugaike Yokoana site, mineralogical characterization was identified based on samples collected from several points (Miyazaki City Board of Education, 2012). The report showed that the stone material of Yokoana tombs is composed of quartz, feldspar, mica, illite, chlorite, and minor amounts of smectite (Figure 6.10). The common swelling behavior is related to specific crystallographic properties of phyllosilicate, especially the smectite group minerals (Ruedrich et al., 2011). Previous studies on the mechanism of damage and swelling behavior of some clay-bearing sandstone showed that cracks may occur on the surface of sandstone due to stress generated inside the sandstone from repeated cycles of dryness and wetting (González et al., 2004; Scherer, 2006). Particularly, if the surface of the wetted stone decreases, sandstone damage that occurs in such a situation is attributable to the mechanisms described by González et al., (2008) who described cracks running perpendicular to the stone surface during the drying process in wet sandstone. Additionally, Du et al., (2018) who studied the deterioration mechanism of the Shimoura sandstone noted that during the drying process cracks may occur on the surface area of the wetted stone material due to generated tensile stresses.

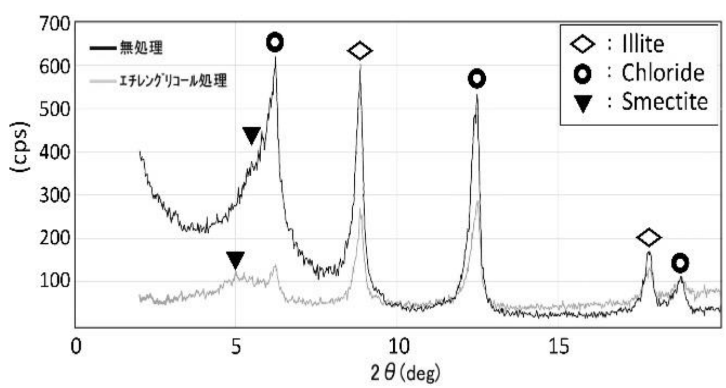


Figure 6.10. X-ray diffraction analysis chart of sandstone used in the Yokoana tomb (© Miyazaki City Board of Education, 2012)

Based on the results of these previous studies, it is evident that the repeated drying and wetting cycles in the Yokoana tombs are significant. Therefore, the tomb walls must be kept constantly dry or moist. There is a source of water for the bedrock to get wet, such as rainwater. Hence, the bedrock of the tombs can be considered as a naturally moist environment. Accordingly, it is impossible to keep the walls of the tomb dry because the sandstone mountain where the tombs are located cannot cut off or decrease the water source. Keeping the walls of the tomb moist can be one of the measures to reduce the stone's deterioration.

6.5.3 Hydrothermal environment investigation of Yokoana tombs

In this study, the outside air temperature, relative humidity, absolute humidity with temperature, and surface temperature inside tombs No.16 and No.17 were measured. Figures 6.11 to 6.15 show the hydrothermal graphics.

Section 6.5.3.1 summarizes the results of the environmental survey during winter and spring, and section 6.5.3.2 summarizes the results of the environmental survey during summer. Section 6.5.3.3 summarizes the correlation between the coefficient of IR absorbance and the moisture content of sandstone as well as the measurement of the moisture content profile on the surface of the wall.

6.5.3.1. Environmental conditions inside the tombs during winter and spring

a) Tomb No.16

The temperature of the lower part in winter and that of the upper and lower parts in spring changed almost the same as the outside temperature (Figure 6.11). The absolute humidity of the lower part closely correlated to the changes in the outside absolute humidity in winter. Further, the absolute humidity of the upper and lower parts were similar to the external absolute humidity in spring (Figure 6.12). The relative humidity of the lower part decreased significantly in winter and that of the upper and lower parts decreased with the external relative humidity during spring (Figure 6.11).

These results indicated that when the tomb is open, internal conditions are largely affected by the natural ventilation through the open entrance. It is clear that the absolute humidity in the tomb was higher than that of the outside air. Therefore, ventilation led to a decrease in the moisture content of the stone wall surface during the above period.

b) Tomb No.17

The temperature of the lower part followed fluctuations in the outside temperature in winter. During spring, the temperature of the upper and lower parts fluctuated slightly (Figure 6.14). The absolute humidity of the lower part changed in the same way as the outside air in winter. However, the absolute humidity fluctuated less than the outside absolute humidity in spring, and the absolute humidity of the upper part followed the outside absolute humidity in the end of spring (Figure 6.15). Regarding the tomb's relative humidity, there was a moisture saturated state, with a frequent decrease in the lower part in winter. In spring, the relative humidity of the upper part was almost moisture-saturated, while the lower part decreased slightly (Figure 6.14).

As per the results, outside air ventilated the lower part of tomb during winter probably through the gaps around the closed door (Figure 6.17). When this tomb's entrance was closed, there was less diurnal variation than tomb No.16.

In this survey, condensation on the wall was examined, which indicated that condensation on the surface of the north wall was suppressed from the middle of September to the end of May for both tombs. All these are considered to be the effects of ventilation in the lower part of the tomb in winter (Figures 6.18 a and 6.19 a). The surface of the lower part of the north wall was constantly moistened during the spring months (Figures 6.18 b and 6.19 b).

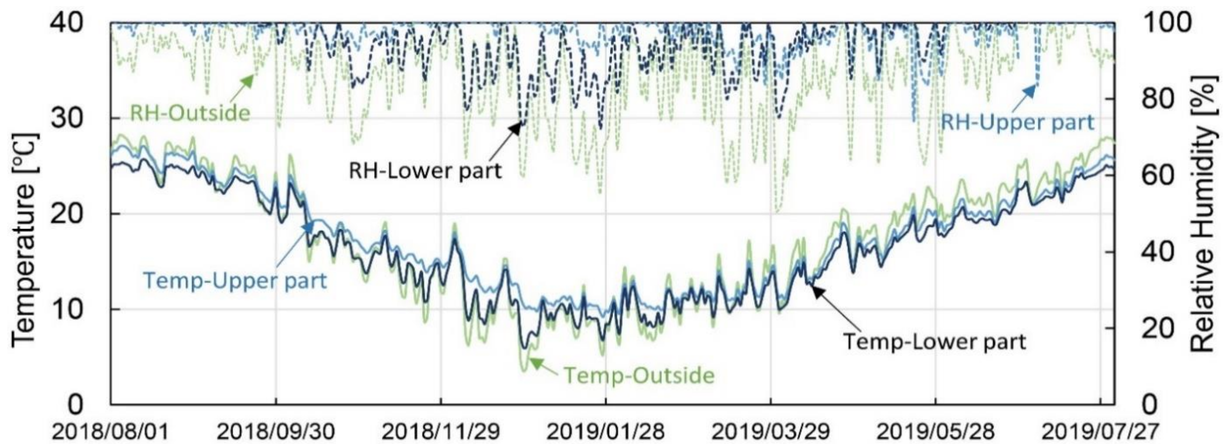


Figure 6.11. Air temperature and relative humidity of tomb No.16

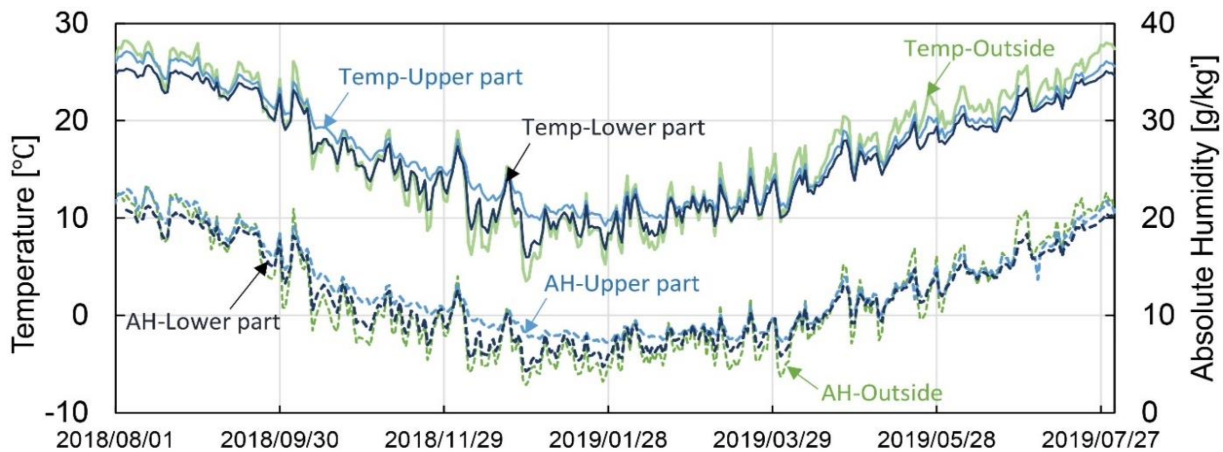


Figure 6.12. Air temperature and absolute humidity in tomb No.16

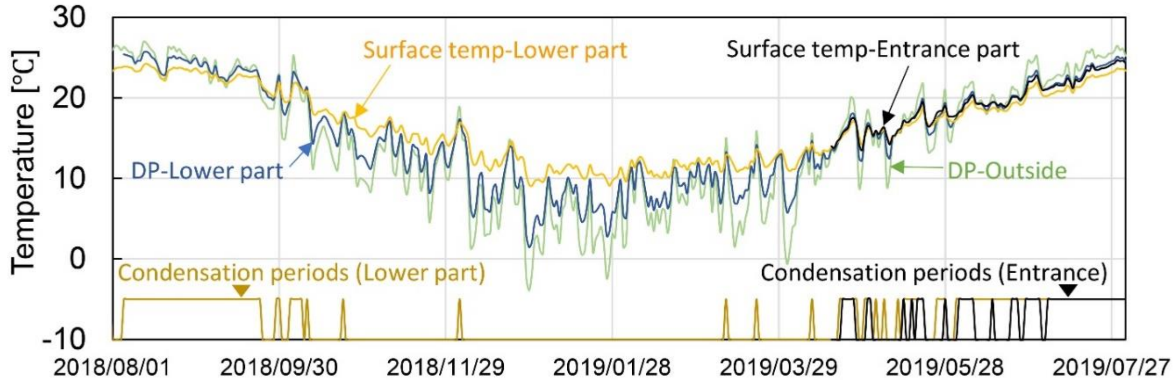


Figure 6.13. Surface temperature and dew condensation in tomb No.16

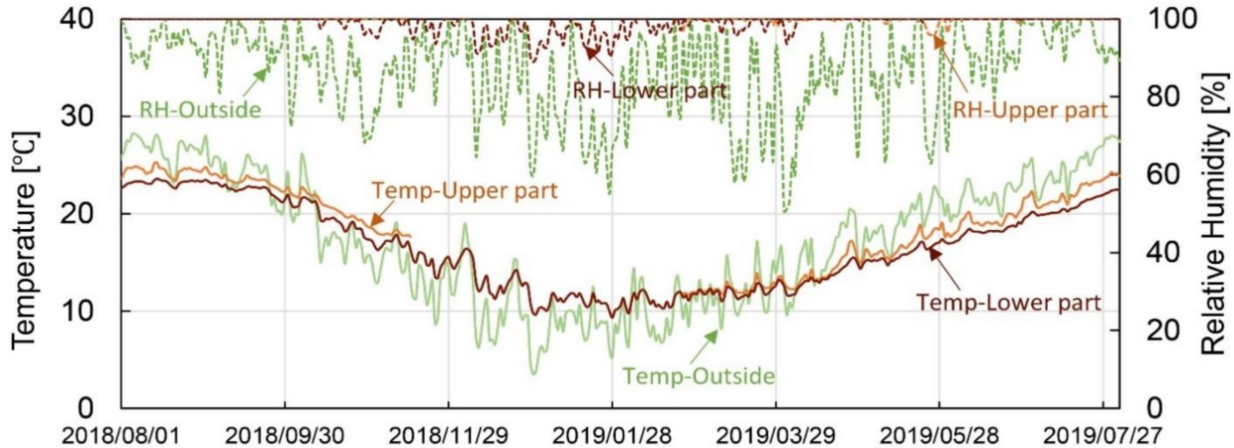


Figure 6.14. Air temperature and relative humidity in tomb No.17

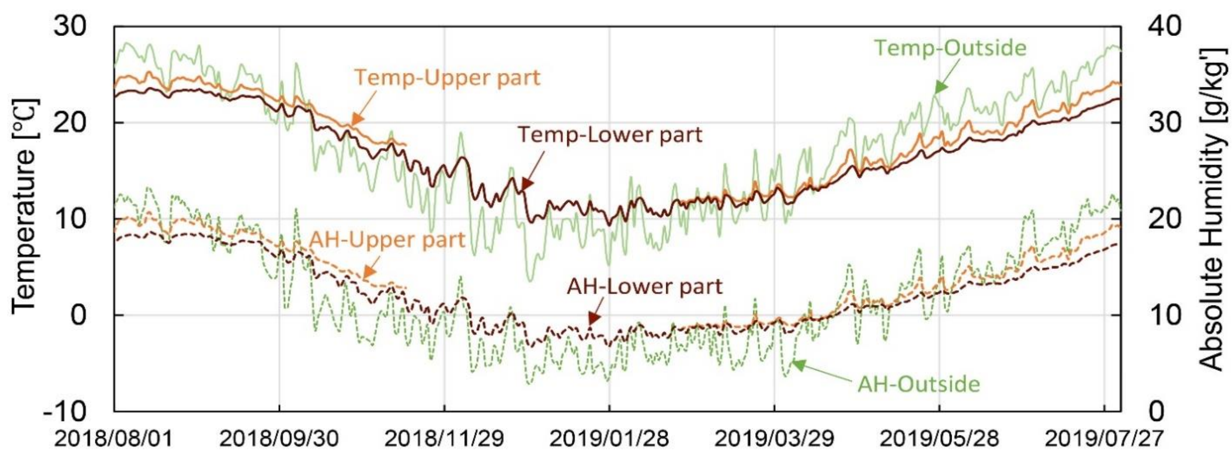


Figure 6.15. Air temperature and absolute humidity in tomb No.17

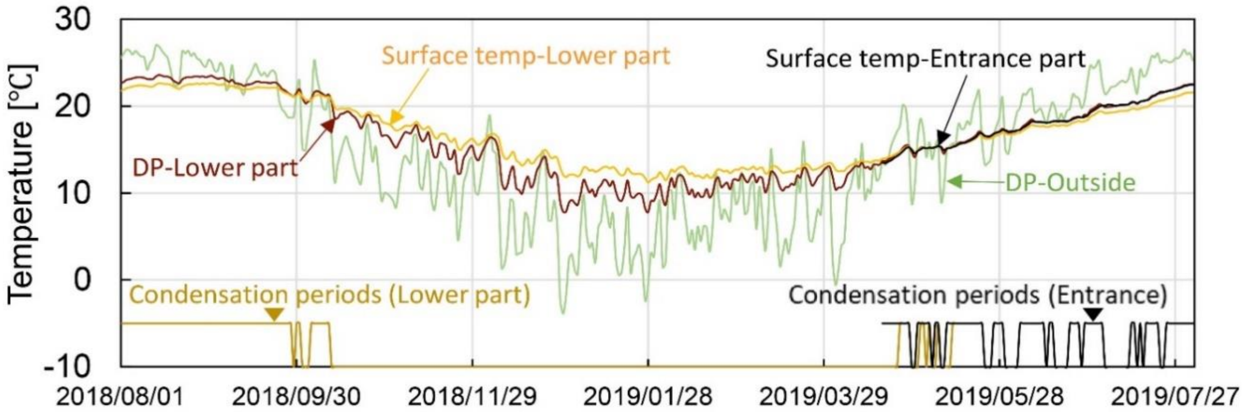


Figure 6.16. Surface temperature and dew condensation in tomb No.17

Figure 6.17. State of the gap between the entrance and the door of the Yokoana tomb No.17. The photo captures the gap from the inside with the tomb closed

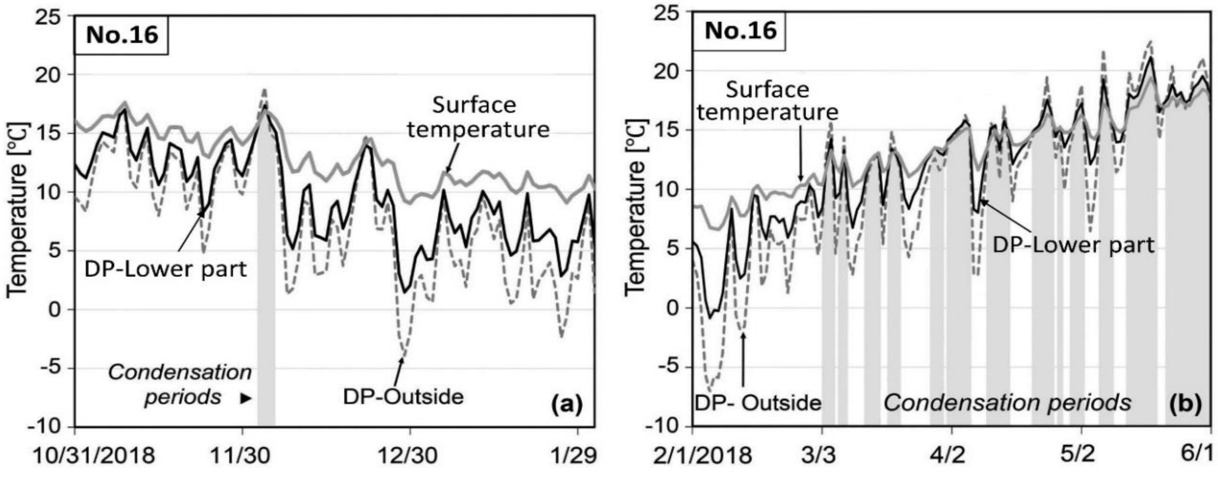


Figure 6.18. Diurnal variations in the indoor dew point at the lower part, rock surface temperature, and dew point outside (DP) Yokoana tomb No.16 (from February 2018 to February 2019). a) Winter, b) Spring, (Gray mark shows the condensation periods)

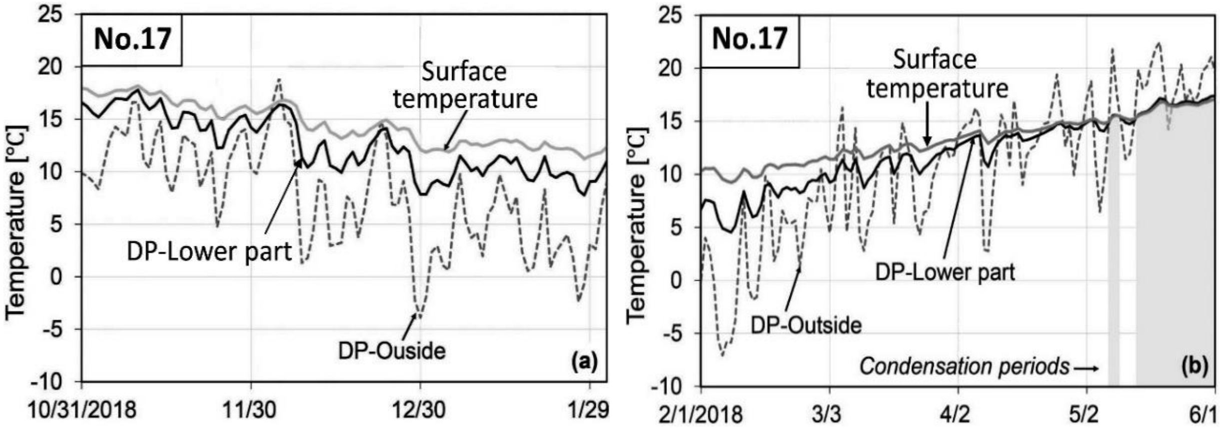


Figure 6.19. Diurnal variations in the indoor dew point at the lower part, rock surface temperature, and dew point outside (DP) Yokoana tomb No.17 (from February 2018 to February 2019). a) Winter, b) Spring, (Gray mark shows the condensation periods)

6.5.3.2 Environmental conditions inside the tombs during summer and beginning of autumn

The temperature of the upper part of both tombs in summer and autumn was influenced by the outside temperature. The absolute humidity of the upper part in summer and autumn was similar to the external absolute humidity (Figures 6.12 and 6.15). The relative humidity of the upper and lower parts of both tombs almost reached a moisture-saturated state in summer and autumn (Figures 6.11 and 6.14).

According to the above results, the outside air slightly ventilated the upper part of both tombs during summer and autumn. The absolute humidity outside was higher than that of the inner tomb. I assume that the highly humid air outside suppressed the humidity of the environment inside the tombs through ventilation circulation.

To examine the condensation on the wall, the surface temperature of the lower part of the tombs during summer and beginning of autumn was measured. The comparison of the surface temperature with dew point temperature, showed that the surface temperature of the lower part of tomb No.17 was below the dew point temperature during the summer and the beginning of autumn. We assume that this environment easily caused dew condensation (Figures 6.20 a, and 6.20 b). During the hydrothermal environment survey, the surface temperature of the lower part of the inner wall of both tombs near the entrance from April to the end of August 2019 was measured. The results indicated condensation and decreasing wet cycles in the lower part of the wall near the entrance within both tombs from the end of spring to mid-July 2019 (Figures 6.13 and 6.16).

6.5.3.3 Measurement of the moisture content profile on the surface of the wall

Waragai et al., (2008) presented the correlation between the coefficient of IR absorbance and the moisture content for sandstone as $w=21.59X$, where w is the water content [%] and x is the coefficient of IR absorbance. Calculations in this study were based on the above linear equation. The results indicated that the correlation of IR absorbance increases linearly with increasing moisture content (Figure 6.21).

The coefficient of the IR absorbance profile on the walls of each tomb was measured every season. The results from the measurements on November 14, 2018 and October 7, 2018 are highlighted in Figure 6.22. Compared to the coefficient of IR absorbance of tombs No.16 and No.17 during the winter periods, the IR absorbance of the walls of tomb No.17 was between 0.500 and 0.900. The coefficient values are marked white, blue, and black in Figure 6.22. It is clear that this coefficient value was higher than the coefficient of the IR absorbance of tomb No.16. Thus, the wall surface of tomb No.17 is determined to have been almost under the condition of water saturation during this period.

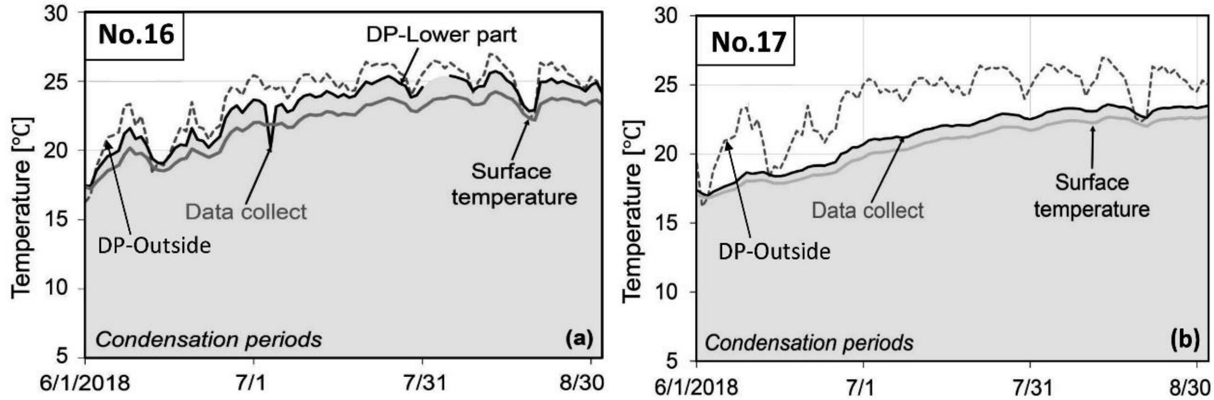


Figure 6.20. Diurnal variations in the indoor dew point at the lower part, rock surface temperature, and dew point outside (DP) Yokoana tomb from June to September 2018. a) Summer (Tomb No.16), b) Summer (Tomb No.17), (Gray mark shows the condensation periods)

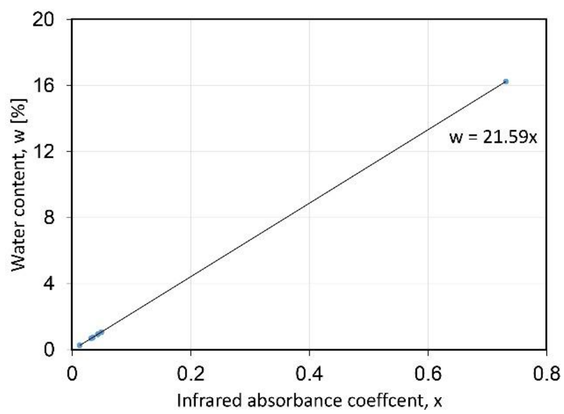


Figure 6.21. Correlation between coefficient of IR absorbance (x) and the sandstone water content (w). Dashed lines accompanied with the equation and correlation coefficient (R) indicate regression lines

6.5.4 Impact of the microclimate and methods of suppressing the deterioration of the tombs

Based on the results presented in sections 6.5.1 to 6.5.3, our investigation about the hydrothermal environment monitoring of both tombs during winter made it clear that the decreasing surface of the tomb walls (lower part) wetting was due to the influence of outside air ventilation during winter. Also, dew condensation and decreasing surface of the tomb walls (lower part and entrance) wetting repeat cycling occurred in spring as well. If the wetted bedrock loses moisture, cracks may occur on the stone surface of the wetted stone material due to generated tensile stresses. Repeated cycles of drying and wetting make microcracks elongate, eventually leading to surface peeling and detachment (Wangler et al., 2008). Therefore, it is necessary to suppress the ventilation frequency during winter and spring.

Although the entrance door to tomb No.17 was closed, there was still some ventilation with outside air entering from the gaps around the door. In this period, evaluation of the changes in the tombs' hydrothermal environment from summer to the beginning of autumn indicated a constantly high humidity when the door was opened and closed. Under these circumstances, condensation indicated on the stone surface. The results of the observation inside both tombs revealed the absence of salt precipitate on the side walls in summer.

Finally, while summarizing the results, it is important to understand that the walls' moisture content increases during summer, beginning of autumn and decreases in winter and spring. This occurs on the tomb walls throughout the year. This drying and wetting cycle was considered to have promoted the deterioration of stone materials. Therefore, to maintain the original surface of the wall, the tomb should be closed from the middle of September to June. Not opening the door of the tomb is a way to curb the deterioration of stone materials. However, the microclimate environment inside the tomb becomes saturated from the beginning of June to the middle of September. During this period, condensation indicated on the surface of the tomb wall and entrance. Section 6.5.2 described the factors of deterioration of Yokoana tombs. Deterioration of the stone may arise during the drying process, where a thin dry layer cracks, running perpendicular to the stone surface under tension (González et al., 2004; Scherer, 2005).

Accordingly, the impact of the deterioration factor mentioned above is minor during the summer and beginning of autumn. Therefore, the tombs can be opened, making it possible to exhibit both tombs to the public from the beginning of June to the middle of September. If the surface of the wall is constantly in a condition of high-water content for a long time, relatively low-solubility salt, such as gypsum may appear on the surface (Arnold et al., 1989).   On the other hand, sedimentary rock contains silicate minerals, including feldspar, mica, pyroxene, and a significant amount of sulfur. One of the forms of gypsum in sandstone is the oxidation of sulfate (Přikryl et al., 2004).

If the moisture in the stone materials evaporates, the origins of the salt are transported to the stone surface, and gypsum may be deposited near the stone surface (Goudie et al., 1997; stone in architecture, 2014). This is considered one of the causes of damage. Further, the conditions mentioned above influence the growth of microorganisms, such as molds and fungus. In case of the Yokoana tombs, this damage may appear on the stone surface for a long time. This, further monitoring surveys in the future must continue to be conducted.

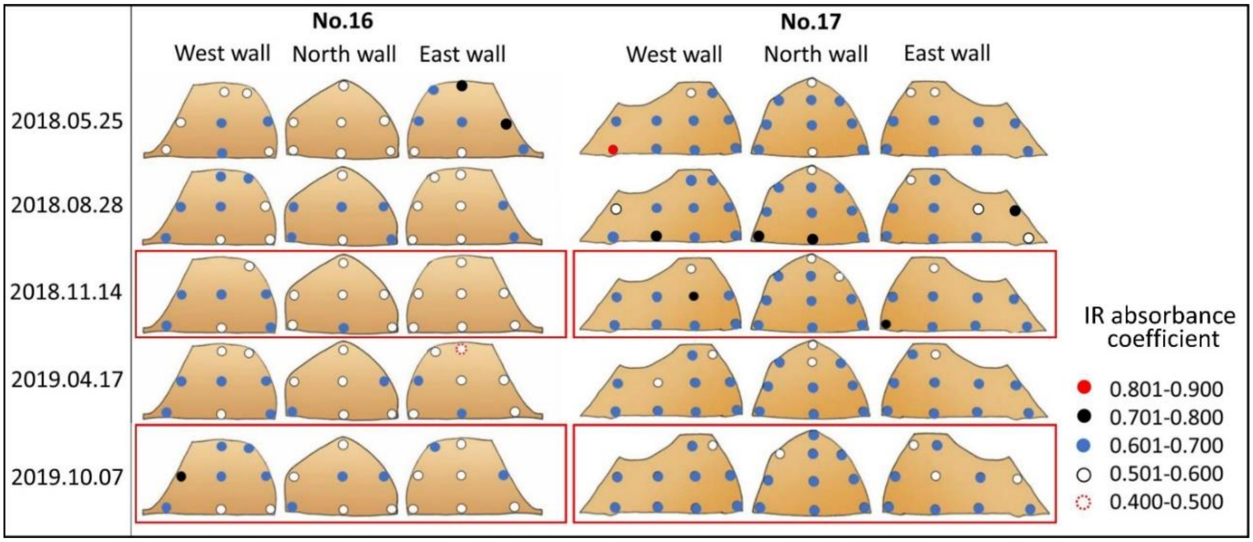


Figure 6.22. Moisture content distribution of Yokoana tombs No.16 and No.17 measured using an NIR moisture meter

6.5.5 Examination of the preservation condition and the thermal environmental survey results after the closure of tomb No.16

The environmental investigation of the inside of both tombs established that during winter, the wall surface wetting decreased when the tomb was open, owing to the influence of outside air ventilation. This surface moisture decrease promoted the deterioration of the stone materials and the peeling of the surface layers of the wall. Based on the above investigation, we decided to seal the door of tomb No.16 during the winter season. On October 7, 2019, based on the investigation results, the Miyazaki City Board of Education closed tomb No.16. Further, surface thermometers were installed around the entrances of tombs No.16 and No.17.

In this section, we discuss the thermal environment of the northern and southern walls (near the entrances) of both tombs and the effect of wetting and drying cycles on the stone surface after the intervention. Figures 6.23 a, b and 6.24 a, b shows the dew point temperatures for the lower part of the tomb and the wall surface temperatures (the lower part of the north wall) of tomb No.16 before and after the closure.

According to the results, the dew point temperature of tomb No.16 closely correlated with the changes in the outside dew temperature in winter. During this period, the surface temperature of the northern wall was condensed several times from October to December 2019 and December to February 2021 (Figure 6.24). As a result of the reduction in the air inflow from outside, the lower part of the temperature fluctuation was significantly less after the closure of the door. Consequently, it was clear that ventilation led to a decrease in the stone wall moisture content. The outside air is assumed to leak in through gaps around the closed door.

Between October 1 and November 30, 2019, and between December 1, 2020, and January 20, 2021, a hydrothermal environmental survey was carried out in tomb No.16. In this survey, focused on controlling the condensation phenomenon on the south wall surface. The results indicated that condensation occurred several times, and the stone material moisture decreased (Figure 6.24). Thus, to reduce the dryness of the wall surface, the space around the door should be kept well sealed during winter months in both tombs.

One of the other factors affecting the reduction of surface moisture in the inner wall of the tomb near the entrance is the phenomenon of heat radiation from direct sunlight. I have taken photo documentation of the solar radiation in the summer and winter inside and outside tombs No.16 and No.17, and I present them in this section (Figures 6.25 and 6.26).

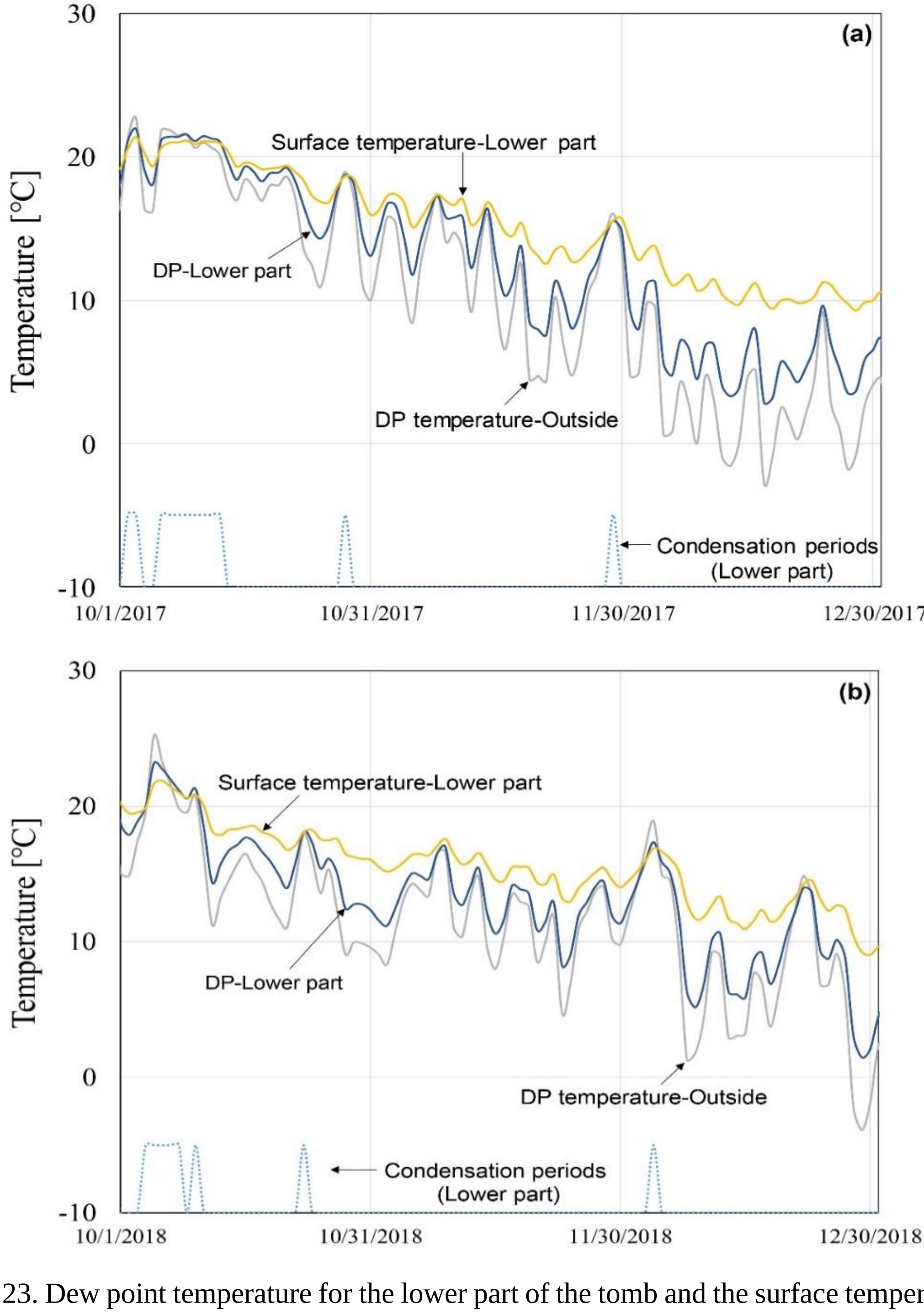
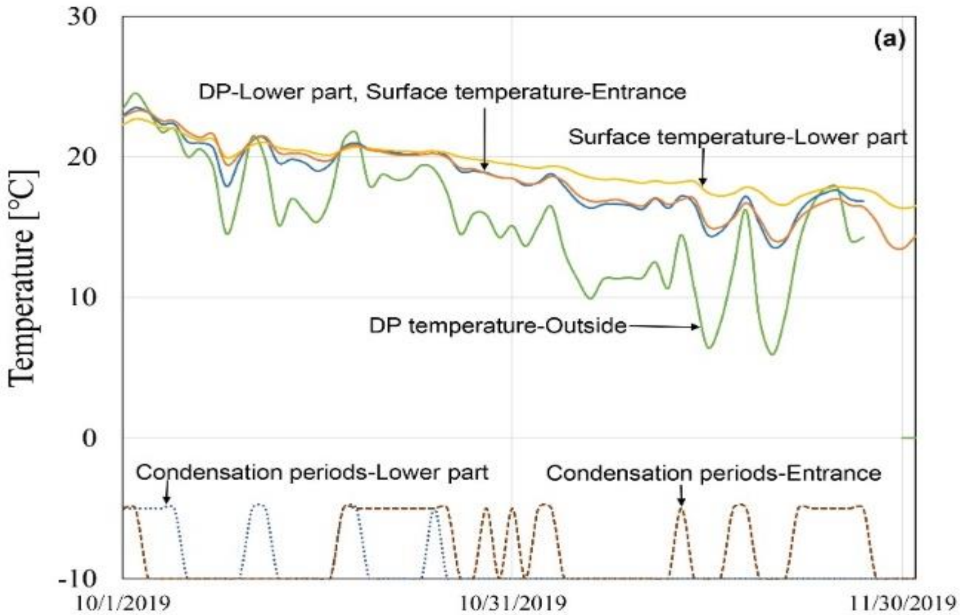


Figure 6.23. Dew point temperature for the lower part of the tomb and the surface temperature (the lower part of the north wall) of tomb No.16 before close. a) October 1 to December 30, 2017, b) October 1 to December 30, 2018



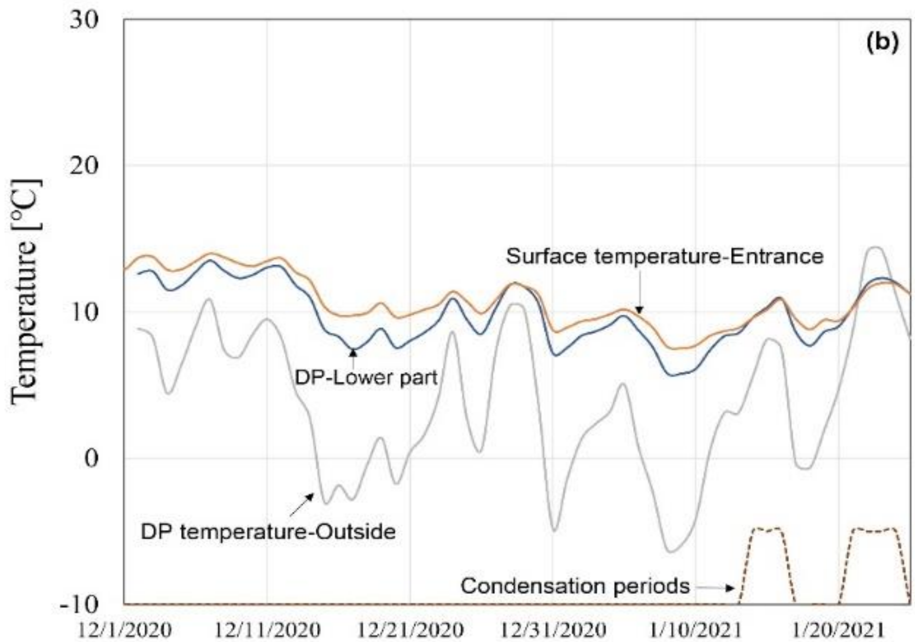


Figure 6.24. Dew point temperature for the lower part of the tomb, the north wall (lower part), south wall (near entrance) of the tomb No.16 after close. a) October 1 to November 30, 2019, b) December 1, 2020 to January 25, 2021

The solar radiation reflected on tomb No.16 in the morning from 9:10 am to 10:30 am on August 28, 2018 (Figure 6.25). To examine the documentation, the solar radiation reflected on tombs No.16 and No.17 from 8:25 am of the morning to 14:40 pm in the mid-afternoon on January 1, 2018 (Figure 6.26). This result indicates that the heat is transferred to the tomb initially by radiation, followed by the flux of heat through the stone material. Therefore, under the influence of the above phenomenon, the moisture on the wall surface may evaporate.

Figure 6.25. Solar radiation insde and outside the tomb No.16 at 10:35 am, August 28, 2018

Figure 6.26. Solar radiation outside the tomb No.16 and No.17

6.6 Summary

In this study, we examined the effects of repeated drying (loss of moisture) and wetting inside Yokoana tombs No.16 and 17. I considered the relationship between the external and internal environment of the tomb, taking into account seasonal factors as well as the effects on the internal environment during phases when the tomb door was open and closed. Therefore, based on the results of the survey, we reached several conclusions:

1) The moisture content of the surface of the tomb wall decreased due to the influence of outside air ventilation in winter and spring. On the other hand, drying and wetting cycles occurred on the wall surface; this is the main factor for the peeling of the stone. In this season, it is better to closed the tombs from the end of the September to the June. This would be effective in reducing deterioration due to the drying and wetting cycles.
2) From June until mid-September, both tombs were saturated, and condensation occurred on the surfaces of their walls. Therefore, the wall surface is considered stable because it was constantly moist during this period. It is thus possible to exhibit the inside of the tombs to the public in this period.
3) Although the entrance door to tomb No.17 was closed, there was still some ventilation owing to outside air flowing in through the door spaces. It is important not only to cover the gap, but also seal it to ensure there is no space remaining.

4) Solar radiation reflected to both tombs during morning and afternoon. Therefore, it will be vital to continue this study in the future, to prevent the wall surface near the entrance of the tomb, from decreasing and losing the moisture due to the heat transfer.

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Chapter 7. Conclusions and outlook

A decorated ancient tomb with full mural paintings was discovered for the first time in Mongolia. The Ministry of Education, Science and Culture of Mongolia planned to preserve the mural paintings at the original site, present the site to the public, and build a museum in the long term. Although, the Mongolian and international teams were carried out risk mitigation and protecting work, consulting services for preservation, documentation activities, and conservation work, the mural paintings continued to deteriorate daily. In the remains that are inseparable from the surrounding environment, there are many cases in which rapid deterioration occurs, such as at the Shoroon Bumbagar tomb.

This is a basic study that focuses on understanding the effects of environmental factors on salt crystallization on mural surfaces, to carry out an intervention to suppress the deterioration of the Shoroon Bumbagar mural paintings. First, the materials used for the mural paintings in the Shoroon Bumbagar tomb were investigated. Second, the physical and biological deterioration that has occurs in the tomb was observed. Next, the influence of the surrounding environment on the microclimate within the Shoroon Bumbagar tomb was examined and the internal environmental changes due to the external environment were assessed by keeping the open dromos closed during the cold season and open during the warm season.

A case study on the conservation measures for the Hasugaike Yokoana tombs in Miyazaki was examined, in order to identify the necessary methods used to preserve the mural paintings of the Shoroon Bumbagar tomb. This chapter provides an overview of the main results of this study. In the outlook, questions requiring future analysis and surveys are discussed.

7.1 Conclusions

Chapter 1 provide an overview of research cases on the mural painting of the tomb and describes the background and aim of this research as well as the structure of this paper.

In Chapter 2, the Shoroon Bumbagar ruin, the geological setting and climate of Mongolia and site were overviewed. Also, in this chapter, the conservation activities carried out at the site were provided.

- Shoroon Bumbagar tomb is located at the south slope of the Maikhan Mountain and is situated at an altitude of about 1100 m above sea level in the Great Khangai Mountain region.
- The underground tomb is composed of a burial chamber, four rectangular airshafts and an open dromos, and the horizontal length from the entrance of dromos to the back wall of burial chamber measures approximately 42 m. Most of the wall has mural paintings.
- The climate condition of the territory where the Shoroon Bumbagar tomb is situated like in any other regions of Mongolia, that is a large annual and daily temperature variation, extremely long, cold and dry winter and short warm summer. The climate classification is a typical continental climate.
- As a result of geological surveys, the landform of the area is apparent, that in 0-0.5 m below ground level there is a dark fertile topsoil layer containing plant roots and humus; in 0.5-1.5 m light gray clay altered schist soil layer; in below 1.5 m light green and grayish blue sand

filled weathered schist alluvial formation. In other words, wall of open dromos are formed from three different soil layers. However, the airshafts and the burial chamber of the Shoroon Bumbagar tomb are located across two basement layers in the alteration zone, which are the light green and, light gray clay weathered schist layers.

In Chapter 3, the structure of the mural painting of the Shoroon Bumbagar tomb was determined, and the composition of the mortar and the pigments used for the mural painting was investigated.

- The mural painting of the open dromos of the Shoroon Bumbagar tomb has three layers such as a paint, ground and mortar. The mural painting of the burial chamber has two layers.
- The red pigment used in the mural painting of the Shoroon Bumbagar tomb was hematite (Fe_2O_3), and the ground layer was calcite ($CaCO_3$). It is necessary to investigate further to clarify the materials in some pigments such as brown, black, and blue used in this tomb.
- Based on the result of experiment on determining particle composition of the mortar used Shoroon Bumbagar mural, gravel was 1.4%, sand was 51.2% and silt and clay were 47.3%. Also, clay contained in the material was less than 5% approximately.

In Chapter 4, the main deterioration commonly seen inside the tomb as well as the results of the observation survey in the burial chamber, airshafts, and open dromos was outlined. The main deterioration observed in the tomb is as follows:

- The lack of cohesion of the bedrock is caused by several factors related to the composition and mechanical properties.
- The wooden propping and planking supporting materials inside the airshafts and burial chamber have a relatively high water content, which can lead to the growth of fungus on the surface. Thus, fungus colonization was attached from the wooden propping surface to the mural painting. In addition, a highly saturated environment for the development of microorganism on the mural painting surface was observed.
- Detachment, peeling of the paint, a ground layer and a mortar layer were observed on the wall surface of the open dromos and upper parts of the airshafts. An x-ray diffraction analysis revealed thenardite. Sodium precipitation was confirmed around the entrance area and the upper part of the open dromos and airshafts. The main reason for this can be explained by the phenomenon of sodium salt crystallization and the high risk of deterioration due to salt efflorescence. On the other hand, in both walls of the open dromos and the upper part of the airshafts, it was confirmed that thenardite was observed on the surface at the beginning of autumn, winter, and spring. The results of the monitoring and documentation of the deterioration showed that the distribution of detachment and the peeling of the preparatory layer spread each. The most active zone of damage to the mural painting was in the middle portion of the western and eastern walls.

In Chapter 5, the influence of the surrounding environment on the microclimate within the shelter, burial chamber, airshafts, and open dromos was examined. Also, the internal environment changes due to the external environment were assessed by keeping open dromos closed during the cold season and opening the open dromos during the warm season. Based on the result of the above survey, we examined the intervention which is suppressing the impact of salt on the walls of the open dromos.

- The results showed relative humidity of the upper part of the burial chamber remained steady at almost 100%, and it became clear that the walls of this area were constantly wet due to condensation. When the surface of the wall is saturated with moisture, the fact that it is a favorable condition for the growth of mold.
- However, the top part of the airshafts is closed during the cold season, and it is clear that there was outside air ventilation following in through the covering material. Thus, ventilation led to a decrease relative humidity of airshaft. Consequently, soluble salt efflorescence would be crystalized on the mural painting's surface. Therefore, it is necessary to suppress the ventilation frequency during the cold season.
- In an open environment during the summer, the relative humidity of open dromos part was almost 100%. Although the high humidity in the open dromos allows for less moisture evaporation from the walls, it would have become a negative effect on the mural's surface, which is a favorable environment for the growth of mold and microorganisms.
- Ventilation of outside air occurred in September, and it is better to close the open dromos and airshafts from the beginning of September.

In Chapter 6, the influence of the surrounding environment on the internal environment of the tombs and determination of the wetting and drying cycles in the tomb due to seasonal changes and the effects on the internal environment during phases when the tomb door was open and closed were examined. Having examined these, we were able to propose better indoor environmental control methods to decrease the deterioration of the tombs and to suggest a method for suppressing its impact. Therefore, based on the results of the survey, the following conclusions were reached:

- The moisture content of the surface of the tomb wall decreased due to the influence of outside air ventilation in winter and spring. On the other hand, drying and wetting cycles occurred on the wall surface; this is the main factor for the peeling of the stone. In this season, it is better to closed the tombs from the end of the September to the June. This would be effective in reducing deterioration due to the drying and wetting cycles.
- From June until mid-September, both tombs were saturated, and condensation occurred on the surfaces of their walls. Therefore, the wall surface is considered stable because it was constantly moist during this period. It is thus possible to exhibit the inside of the tombs to the public in this period.
- Although the entrance door to tomb No.17 was closed, there was still some ventilation owing to outside air flowing in through the door spaces. It is important not only to cover the gap, but also seal it to ensure there is no space remaining.
- Solar radiation was reflected into both tombs during the morning and afternoon. Therefore, it will be vital to continue this study in the future, to prevent the wall surface near the entrance of the tomb from losing moisture due to heat transfer.

In conclusion, the influence of the surrounding environment on occurrences inside the open dromos, airshafts, and burial chamber of the Shoroon Bumbagar tomb has been clarified within the scope of the study on the conservation of a decorated ancient tomb in harsh climatic condiion.

In particular, I focused on the deterioration of the mural paintings caused by salt crystallization and aimed to clarify the mechanisms and measures taken to stabilize and suppress salt crystallization. The results of this study can be summarized as follows:

1) The area where the Shoroon Bumbagar tomb is located contains natural saline. The main deterioration of mural paintings is due to salt crystallization; consequently, the mortar layer used in the mural paintings is easily destroyed by salt precipitation. The salt deposited on the mural painting is Na_2SO_4 (Thenardite). The salt precipitation phenomenon was also observed in the open dromos from the end of August to June; however, the open dromos were closed during the cold season. The study clarified that the salt crystallization of Na_2SO_4 is greatly affected by the increase of water evaporation from the soil by the cold and dry air ventilated through the first airshaft in the cold season.
2) As a result of examining the measures to suppress salt precipitation, the passing corridor of the open dromos was sealed, and the air ventilation frequency from the first airshaft was reduced. It was shown that the deterioration of the mural paintings in the open dromos due to salt crystallization could be significantly suppressed.

As mentioned above, the geological structure and soil properties of the site where the tomb is located, and the materials used in the mural paintings provide significant information for the preservation of underground tombs in harsh climates. In addition, the indoor environment of the tomb should not be exposed to outside air or cold air during the cold season. Due to the above effects, physical damage will be caused by salt crystallization, and repeated drying and wetting cycles, therefore careful consideration should be given to the time of entry and opening of the tomb, to avoid, outside air ventilation as much as possible. The study on how to preserve decorated ancient tombs in harsh climatic condition, can make a significant contribution to the preservation of cultural heritage.

7.2 Outlook

- Research has shown that it is hazardous to preserve the Shoroon Bumbagar mural paintings in the tomb; thus, immediate action must be taken to prevent further collapse and destruction of the mural. Therefore, the focus will be on laboratory experiments exploring how to protect the murals when reburying the tomb or researching and developing methods that minimize the risk of removing the mural.
- The geological formation of the site of the Shoroon Bumbagar tomb is composed mainly of weathered gravel, and the water content is high due to silt and clay at a depth of 2 m from the ground surface. This layer of silt and clay freezes during the cold season (from autumn to spring) and when this happens, it can promote flaking and collapsing in the mural painting. Therefore, further studies on the effects of freezing and thawing cycles are required.

- Based on the results of the environmental survey in the Hasugaike Yokoana tombs, repeated drying and wetting cycles were believed to have promoted the deterioration of the stone materials. However, keeping the walls of a tomb moist can be one of the measures to reduce stone deterioration. Although this is one way to reduce the repeated drying and wetting cycles, when the surface of the wall is saturated with moisture, it is likely to influence the growth of microorganisms and gypsum on the stone surface over a long time. Therefore, it is necessary to conduct adequate monitoring and interventions in the future.

List of publication on this research

Published Paper

1. Angaragsuren O. and Kohdzuma Y. 2018 “Study on the conservation of mural painting in Mongolia: Microclimate analysis of the indoor environment and scientific investigation of painting materials used in the mural painting of the Shoroon Bumbagar tomb”, Journal of Studia Archaeologica. Tom. (I) XXXI, Fasc.12, Ulaanbaatar, pp.207-217

2. Angaragsuren O. and Kohdzuma Y. 2020, “Investigation of the pigments and materials used in some mural paintings of Mongolia”, Journal of Conservation Science, vol.59, Independent Administrative Institution Tokyo National Research Institute for Cultural Properties, pp.115–131

3. Angaragsuren O., Wakiya S., Yanagida A. and Kohdzuma Y. 2021. “Preservation and exhibition of the Hasugaike Yokoana tombs based on environmental survey” Journal of Cultural Heritage Study, Vol. 82. pp-63-77

Academic conference (Oral presentation)

1. Angaragsuren O. and Kohdzuma Y. “Study on the conservation of mural painting in Mongolia: Microclimate analysis of the indoor environment and scientific investigation of painting materials used in the mural painting of the Shoroon Bumbagar tomb”, Mongolian Archaeology Conference-2017, Mongolian State University, Ulaanbaatar, Mongolia. 2018.02.1-2

2. Angaragsuren O. and Kohdzuma Y. “A study of the deterioration and material of the mural painting which is preserved in the museum”, Mongolian Archaeology Conference-2018, Ulaanbaatar University, Mongolian Science Academy, Ulaanbaatar, Mongolia. 2019.01.24-25

3. Angaragsuren O., Akinobu Y., Wakiya S. and Kohdzuma Y. “Investigation of the environment in the Hasugaike Yokoanagun tombs” 35th Annual Meeting of the Japan Society for Scientific Studies on Cultural Property, Nara Women’s University, Nara, Japan. pp. 68-69, 2018.07.6-7

4. Angaragsuren O., Enkhbat G. and Kohdzuma Y. “Monitoring and Investigation of the microclimate environment in the Shoroon Bumbagar tomb” 36th Annual Meeting of the Japan Society for Scientific Studies on Cultural Property, Tokyo University of the Art, Tokyo, Japan. pp.14-15, 2019.06.1-2

5. Angaragsuren O., Munkhtsetseg B. and Kohdzuma Y. “Materials and deterioration of mural painting of the tomb stored in the museum” (in Mongolian), “Training and education of Mongolian traditional style of painting, pressing issue” academic conference, Mongolia State University of Culture and Art, Ulaanbaatar, Mongolia. pp. 27-50, 2019.10.14

6. Angaragsuren O. “Technical and material analysis of the wall painting of the Shoroon Bumbagar tomb, “Development of Mongolian Fine Arts and Design” academic conference, Mongolia State University of Culture and Art, Ulaanbaatar, Mongolia. pp.27-50, 2020.10.20 (in Mongolian)

Poster presentation

1. Angaragsuren O. and Kohdzuma Y. 2017 “Study on conservation of mural paintings in Mongolia: Scientific investigation on painting materials used for Shoroon Bumbagar mural painting”, Traditional Techniques and Modern Technology: the proceeding of the sixth symposium of the Society for Conservation of Cultural Heritage in East Asia, Fudan University, Shanghai. pp.473-481
2. Angaragsuren O., Furumatsu T., Matsukawa T. and Kohdzuma Y. 2019 “Investigation of pigments used in mural paintings of Mongolia”, 36th Annual Meeting of the Japan Society for Scientific on Cultural Property, pp.178-179

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