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Long-term evaluation of the conservation state of marble statues

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Abstract

Based on comparative investigations after a period of six years, a reduction of the ultrasonic velocity of 9% and 11% for two marble statues could be detected. The investigations on the objects were based on a newly implemented monitoring program using checklists and detailed mappings to document the development of the conservation state of the monumental statues in the historical center of Berlin, Germany. Traditional ultrasonic measurements were combined with surface hardness tests for selected representative areas using an equotip 3 device. In these areas, the water absorption was tested as well, using Karsten test pipes. In some areas and for different states of weathering, the results show a clear correlation between the surface hardness and the measured ultrasonic wavelength. The results of the water absorption tests underlined the differentiation of weathering forms. The investigations can help to characterize and distinguish between different forms of weathering, such as structural depth weathering or a softening close to the surface. By comparing the nondestructive and only minimal invasive test results with petro-physical compressive strength measurements of marble samples, a clear correlation between ultrasonic velocity, surface hardness, and capillary porosity could be identified. The results can help to calculate the stability assessment, plan the conservation, and make a prognosis of the ongoing weathering process. In conclusion, we elaborate a concept for conservation and restoration and make recommendations for a sustainable preservation of the sculptures.

Keywords: *Ultrasonic velocity, Surface hardness, Weathering forms, Conservation*

1. Introduction

For over 30 years, stone conservation has used ultrasonic measurements to evaluate the conservation state of marble. Today, making regular measurements can determine the state of conservation and the progression of the weathering process. A reduction of the ultrasonic velocity could be evaluated in most cases measured on marble statues in Munich and Potsdam (Köhler, Snethlage 2013; Pamplona, Simon 2012). Over a period of circa 20 years some of the most important marble statues in Berlin were investigated.

2. Objects of investigation

This study focuses on the marble statues of Generals Bülow and Scharnhorst, located in the historical center of Berlin, Germany. The Prussian generals Friedrich Wilhelm Bülow von Dennewitz (1755-1816) and Gerhard Johann David von Scharnhorst (1755-1813) played an important role in the German campaign of the Napoleonic Wars, 1813-1814 (in Germany also known as the European Wars of Liberation). Scharnhorst was also a key figure in the reform of the Prussian military. The sculptures are made from Carrara marble and are generally regarded as masterpieces of the important nineteenth-centruy “Berlin School” of sculpture. They were created by Christian Daniel Rauch (1777-1857), one of the most important sculptors of German classicism.

2.1. Rock material

Both sculptures are made out of nearly sculpture-quality white Carrara marble. Macroscopic observations show that the material of the Scharnhorst sculpture seems to have a finer crystalline structure than the Bülow sculpture. The crystal size of the marble of the Scharnhorst sculpture is about 300 μm, and the crystals are mostly polygonal and slightly curved in form. The material of the Bülow sculpture has a smaller crystal size of around 200 μm. The crystal form again is polygonal but essentially straight.

2.2. History of conservation and restoration

The two sculptures have had a troubled history that has been documented in detail by the Berlin Federal State Office for the Protection of Monuments: In 1822 the sculptures were placed to the left and right of the “Neue Wache” (new guard house). The building on “Unter den Linden”, the main avenue in the historical center of the city, was formerly the main royal guard house and was built according to plans by Karl Friedrich Schinkel (1781-1841).

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It is almost a miracle that the sculptures survived the Second World War, protected by a protective wall surrounding each monument. In 1950 the socialist government of the GDR had the monuments disassembled for political reasons, on the occasion of a meeting of its youth organization.

Both objects were stored on the nearby Museum Island. The Bülow sculpture was restored between 1954-58 for the first time, the Scharnhorst sculpture in 1960. In the case of the Scharnhorst sculpture, the eagle, the heraldic animal of Prussia was removed and the whole monument moved across the street from the historical location one year later. The Bülow sculpture remained in depot. In 1990 the Scharnhorst sculpture was brought to the state restoration workshop, restored and afterwards stored in another depot. Twelve years later both sculptures were placed back on “Unter den Linden”, this time not at their historical location but rather across the street, again for of political reasons. Politics again was the reason why unknown perpetrators threw bags of paint on both sculptures during an anti-militarist demonstration in 2005. The sculptures were cleaned the same day on the request of the police, in accordance with a police directive to remove graffiti in the historical center within 24 hours. The cleaning was carried out using high pressure that caused damage to the surface. The next and last restoration of both sculptures was done one year later.

Figure 1. The “Neue Wache” building with the sculptures general Bülow (left) and Scharnhorst (right) around 1900.

2.3. Monitoring program and state of conservation

The Berlin Federal State Office for the Protection of Monuments saw itself moved to designate the long-term maintenance of the public bronze and marble statues in the centre of the city as a pilot project because of their outstanding artistic, historical and urbanistic value which has been implemented since 2009 and is the only such program of its size in Germany (Rieffel 2009). The program includes damage mappings, yearly inspections, and collecting of all relevant data into checklists and reports.

Both sculptures show similar forms of weathering. These include the crumbling of crystals, disintegration, relief formation, and discoloration combined with microbial growth (Fig. 2). The different forms of weathering were mapped during the first monitoring campaign in 2009 by restorer E. Böhme and a conservation action plan developed in 2013. Some of the damage to the surface can be traced back to the unsuitable cleaning campaign in 2005. In general the weathering of marble is caused by hygrothermal stress, solution decomposition, and frost bursting (Rüdrich 2003).

3. Measurement equipment and methods

For the ultrasonic measurements two different signal transmitters were used. The sculptures were investigated using a compressive wave transmitter with 250 kHz (area-shaped), the pedestals with 48 kHz (point-shaped). First the system USG 30 of the Geotron company was applied, and the objects measured by the method of longitudinal ultrasonic waves in direct transmission. The accuracy of measurements using this system is assumed to be 10%. During the measurements the transducers were coupled to the surface with suitable clay material. To evaluate the condition of the material the classification system formulated by Köhler 1991 was used (Table 1).

For surface hardness tests, an equotip 3 (proceq) portable testing device was used. The instrument offers extended capabilities such as measurements on almost all part geometries, with a high accuracy of ± 4 HL (0.5% at 800 HL) with automatic correction for impact direction. For each investigated area 10 individual measurements were done and the average value calculated. Capillary water uptake tests were done with Karsten test pipes and distilled water.

Table 1. The ultrasonic wave velocity related to the condition and the porosity of marble, following Köhler 1991.

class	p - wave velocity v_p (ms^{-1})	condition	porosity (%)
I	> 5000	fresh	< 0,5
II	3000 - 5000	increasingly porous	0,5 - 1,3
III	2000 - 3000	sanding	3,0 - 1,3
IV	1500 - 2000	fragile	3,0 - 5,0
V	< 1500	disintegration	> 5,0

3.1. Measurements and test areas

The sections, distances, and values of ultrasonic measurements in 2006 were documented in detail by Jörg Rüdrich. For the comparative investigations in 2013 the same sections as in 2006 were measured using the same equipment. In addition, areas of different representative states of conservation were documented with a portable digital microscope with 50x enlargement (Fig. 2), and tested by surface hardness using the equotip devise. These areas also were measured by ultrasonic velocity. During both campaigns the investigations took place in a period of dry weather.

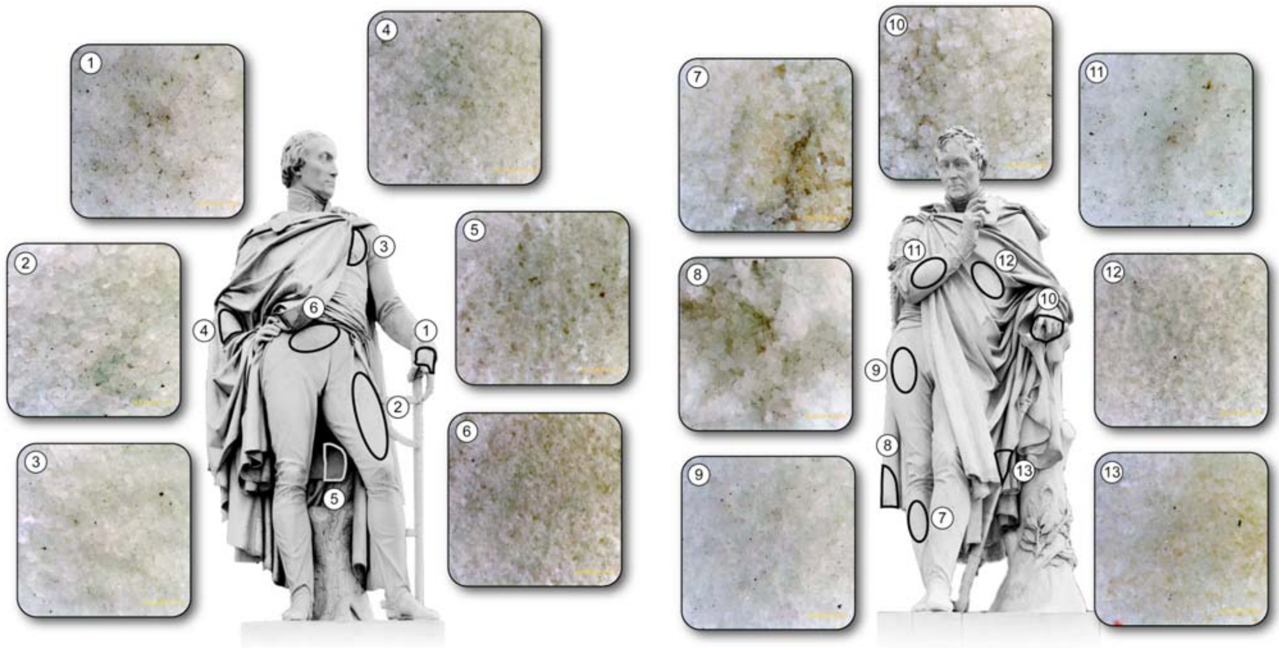

Figure 2. The surfaces of both marble statues show different conditions: 1) separation of crystals and formation of a relief, 2) weathered surface showing single crystals and a low relief formation, 3) moderate weathering, 4) moderate weathered area with microbial growth, 5) and 6) low weathered, nearly intact area with dirt deposits,7) and 8) strongly back-weathered area with microbial growth, 9) moderately damaged surface, 10) separation of crystals by weathering and formation of a relief, 11) moderately weathered area, 12) nearly intact area, and 13) weathered surface.

3.2 Results of the measurements of the Bülow sculpture

The results of ultrasonic velocity measurements in 2006 showed values between 2,1 km/s and 4,1 km/s. The average value of all measurements is 3,40 km/s. In contrast to 2006, the measurements in 2013 showed values ranging between only 1,6 km/s and a maximum of 4 km/s. The average value reached 3,06 km/s, which amounts to a reduction of 11%. A clear reduction of the ultrasonic velocity could be detected for sections with a material diameter smaller than 20 cm (Fig. 3). Most notable is the change of the ultrasonic velocity of the pommel of the sword. This pommel was replaced during the restoration in 2005. In 2006 a value of more than 5 km/s could be measured. Seven years later only 3,13 km/s was detected, which amounts to a reduction of around 40%.

The surface hardness ranges between 291 and 564 HLD. Most values of surface hardness of the tested areas (1, 3, 5, and 6) show a good correlation with ultrasonic velocity (Fig. 4), and therefore indicate a penetrative lost of strength also related to surface weathering. The measurements of areas 2 and 4 with around 350 HLD show quite low values of surface hardness but an ample ultrasonic velocity of on average nearly 4 km/s and a classification of II following Köhler. This area of the original surface is well protected against direct wind and rain but the crystal structure is weathered (Fig. 2 [2,4], 4).

Capillary water absorption, tested by Karsten test pipes only could be detected for area 1. This area has had the lowest HLD values (291) and as well the lowest ultrasonic velocity (1.6 km/s), which means it reached nearly the classification I (disintegration).

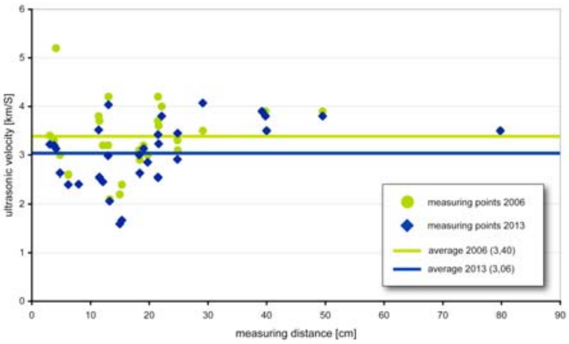

Figure 3. The ultrasonic velocity related to the distance of measurement.

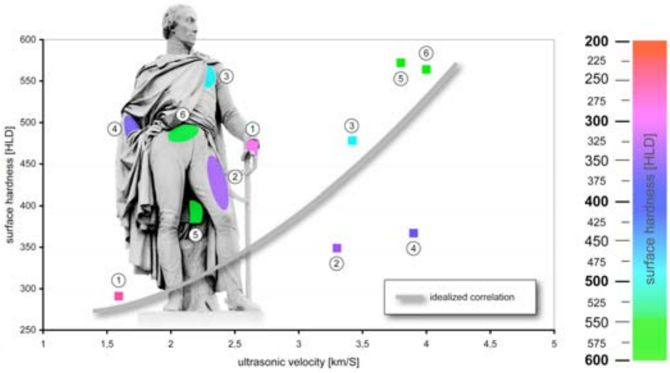

Figure 4. The surface hardness correlated with the ultrasonic velocity.

3.3. Results of measurements of the Scharnhorst sculpture

In a first campaign the sculptures were measured by ultrasonic velocity in 2006 after the last restoration. The sculpture show values between 2,5 km/s and 4,6 km/s and are reaching a average of 3,66 km/s. By the comparative measurements in 2013 values between 1,4 km/s and 4,4 km/s and an average value of 3,4 km/s could be detected. This comparative low weakening of the average value amounts to a reduction of 9%.

The highest values between 4,0 km/s and 4,6 km/s could be detected at compact areas such as the trunk of the sculpture. In 2006 as well in 2013 low ultrasonic velocity between 3,0 km/s and 4,4 km/s could be measured on free weathered arms and legs. Following the classification of Koehler, these areas are increasingly porous (II). The lowest values could be detected at filigree details such as fingers and robe folds. In 2006 these areas reached an average value of only 2,5 km/s. In 2013 an average value of only 1,7 km/s could be measured for these areas. The results show clear reduction of the ultrasonic velocity for sections with a material diameter smaller than 30cm (Fig. 5). This may be due to a deeper penetrative weathering that developed in the case of the Scharnhorst sculpture, probably because the sculpture was exposed to weathering 27 years longer than the Bülow sculpture.

Surface hardness varies between 300 and 450 HLD. Nearly all values of surface hardness measurements show a good correlation with the ultrasonic velocity (Fig. 6). This indicates a relation of the lost of structural and surface strength and supports the thesis of a penetrative structural weathering. Only the measurements of area 7 with around 450 HLD show high values of surface hardness but only a medium-sized ultrasonic average velocity of 3.1 km/s. This area of the original surface is water-proofed and still in good condition while the ultrasonic value indicates that a structural weathering has also affected the area.

Capillary water absorption, evaluated by Karsten test pipes could only be detected in area 1. This area has the lowest HLD values (300) and the lowest ultrasonic velocity (1.8 km/s), reaching the classification IV (fragile) following Koehler (Fig. 6, Tab. 1).

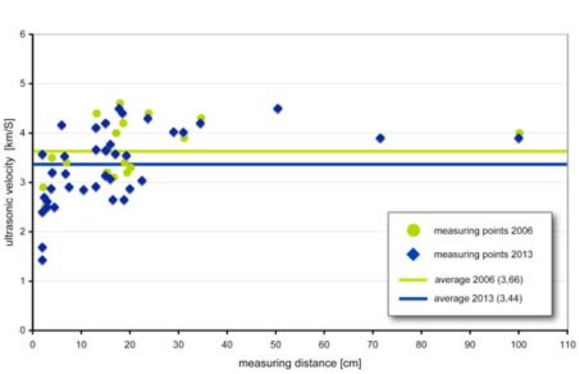

Figure 5. The ultrasonic velocity related to the distance of measurement.

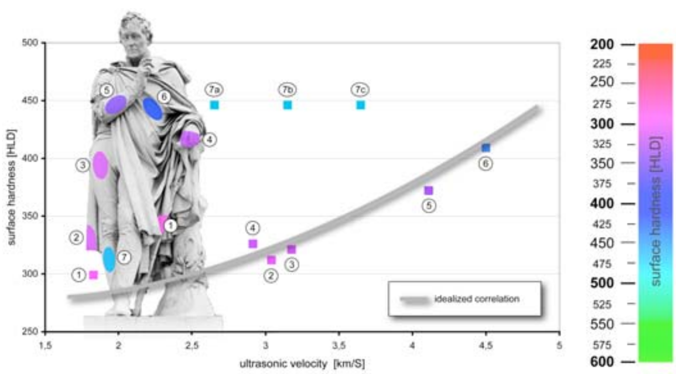

Figure 6. The surface hardness correlated with the ultrasonic velocity.

4. Discussion

With the combination of the testing methods used different forms of weathering could be distinguished. If only low ultrasonic velocity and low surface hardness values are measured it can reasonably be concluded that the tested area is affected by a structural, penetrative depth weathering. This could be measured in case of the Bülow sculpture at area 1 and for the Scharnhorst sculpture at areas 1 – 4 (Fig. 4 & 6). If water absorption also occurred in these areas, then the situation is in an acute critical condition. If the surface hardness values are high but ultrasonic values are only low, also depth weathering could be combined with the formation of a crust, for example due to dissolution of calcite and precipitation at the surface. If the surface hardness shows low values but the material a high ultrasonic velocity, the damage only is located at the surface. This is the case for example at the areas 2 and 4 of the Bülow Sculpture. This damage can be traced back to the unsuitable cleaning with a high-pressure cleaner in 2005.

For the investigated samples of Carrara marble in different conditions, in a comparison of samples from both sculptures a compressive strength of 40.89 N/mm^2 for weathered samples and of 105.52 N/mm^2 for non-weathered ones could be detected (Rüdrich et al. 2013). In the cited study the authors also presented a clear correlation between ultrasonic velocity and compressive strength. By fitting the measured values of the ultrasonic velocity into the diagram of Rüdrich et al. 2013, the average compressive strength of the Bülow sculpture can be determined to be around 95 N/mm^2 in 2006 and 90 N/mm^2 in 2013. The changes become clearer when looking at the results for filigree parts of the sculpture. For these areas a reduction by half up to a maximum of around 60 N/mm^2 and a minimum of around 30 N/mm^2 can be assumed (Fig 7[a]). For the Scharnhorst sculpture it looks quite similar: the average value reaches around 100 N/mm^2 in 2006 and 95 N/mm^2 in 2013 but the affected filigree details of the sculpture show a reduction even higher than the for the Bülow sculpture (Fig 7[b]). Possibly this can be traced back to its sustained period of outdoor exposure over a period of 27 years. The Scharnhorst sculpture was exposed to weathering for 117 years, the Bülow sculpture for 90 years.

The reduction of compressive strength and loss of material stability seems to be concentrated on the parts with a low material thickness and was presented already as a model as one result of a scientific project to evaluate the state of conservation of the marble statues on the castle bridge in Berlin (Fig, 8; Rieffel 2010). The same weathering forms could be observed in the case of the measuring result of both sculptures in this study.

Furthermore it becomes clear that even fresh material (like the pommel of the sword of the Bülow statue) shows a significant deterioration within the first years of outdoor exposition. Related observations were made in the case of the distortion of cladding panels from marble (Koch 2005). These panels show the biggest distortion within the first years followed by a continuous but weak deformation.

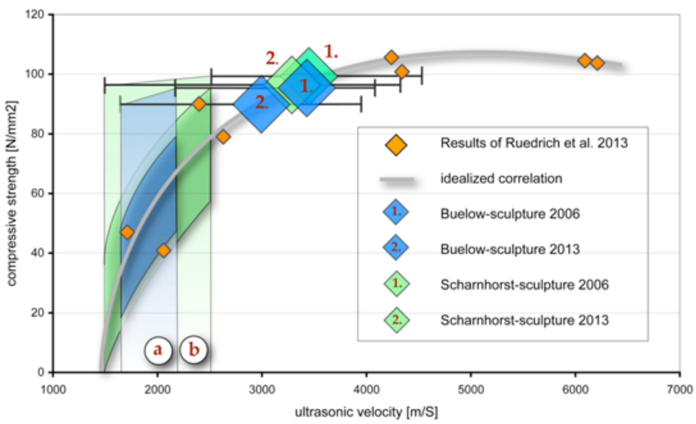

Figure 7. The results of the ultrasonic measurements inserted into the diagram of Rüdrich et al. 2013. The average values of the Bülow sculpture show lower ultrasonic velocity but a lower decrease of stability loss a) than the Scharnhorst-sculpture, b).

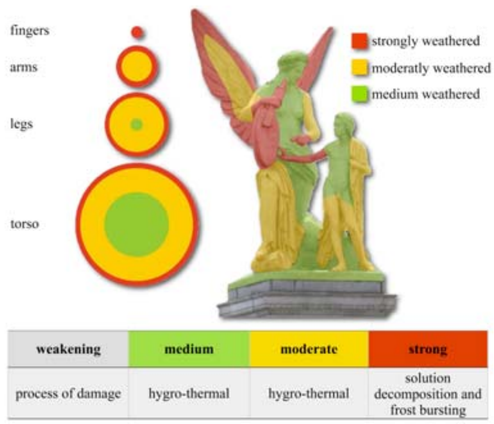

Figure 8. Model of the loss of stability dependent on the object geometry.

Only within the strongly weathered areas with an ultrasonic velocity of less than 2 km/s and a classification following Köhler of IV to V (Tab. 1) water was absorbed by capillary action. These areas show a low compressive strength between 20 N/mm^2 and 60 N/mm^2 connected to a surface hardness up to 300 HLD.

4.1. Conservation

The results of investigation have consequences for conservation, because only the strongly weathered areas can be treated by conventional methods. To ensure that a consolidation material is able to penetrate into areas with a damage class of III or II, vacuum impregnation methods have to be used.

One of these methods is the Acrylic Total Impregnation (ATI), developed by Wolf Ibach and successfully applied in many cases since the 1970s (Sobott, Ibach 2008). Monolithic marble sculptures were treated successfully, as could be proved by several ultrasonic velocity measurements after different periods of time (Pamplona, Simon 2012). The results presented in the latter article also show that after several years a weakening of the ATI-treatment can be detected.

When using the ATI-procedure, one aspect that has to be kept in mind; marble has a relative high thermal dilatation of calcite, and the anisotropic behavior of the calcite-crystal is well known (Kleber 1959). The calcite-crystal shows an anisotropic thermal dilatation coefficient (α) of $\alpha = 6 \times 10^{-6}$ in one and $\alpha = 26 \times 10^{-6}$ in the other direction. Thermal stress causes a physical loosening of crystal boundaries, deformation, and weathering (Siegesmund et al. 2000). Acrylic resins show a much higher thermal dilatation, ranging between 50 and 110 x 10^{-6}/K, around 5 times higher than calcite, which can lead to an increase of dilatation that bears the risk of causing damage. The highest effect on dilatation change at 60°C with an increase that reached between 0,4 to 0,6 mm/m around the double of an untreated sample (0,18 - 0,3 mm/m) could be observed in case of Carrara marble (Rüdrich 2003). Today, problems can be observed within the joints of the Beethoven-Haydn-Mozart-monument, located in Tiergarten/Berlin. The monument was made of marble and treated with ATI in 2007. Today nearly all joints are cracked or lost only 6 years after restoration. The biggest gaps can be observed in joints of the south-facing monument, leading to the assumption that the increase of thermal dilatation could be the reason. The biggest gaps can be found between old treated stone blocks and new untreated ones. Using the ATI-treatment for the two sculptures described in this paper could cause risks, because today many details were replaced by new marble during different campaigns of restoration. Today, both sculptures are no longer monolithic sculptures. To protect these important sculptures in the future, the possibility of producing new copies and placing the originals in a museum is being considered.

5. Conclusions

The investigations show that different parts of a sculpture weather in different forms and at different speeds. The combination of different investigations such as ultrasonic velocity, surface hardness, and water uptake tests can help to characterize and distinguish between different forms of weathering, such as structural, penetrative depth weathering or a softening close to the surface. By comparing the results of the nondestructive or only minimally invasive test methods with petro-physical compressive strength measurements of marble samples, a clear correlation between ultrasonic velocity, surface hardness, and capillary porosity could be identified. The results can help to calculate the stability assessment and make a prognosis of the ongoing weathering process. A highly detailed knowledge about the conservation state of an object makes it possible to develop the right conservation strategy.

6. References

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