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WEATHERING AND DETERIORATION OF BUILDING STONES IN TEMPLO MAYOR, MEXICO CITY

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Abstract

Templo Mayor Archaeological Site, the remains of the ancient ceremonial precinct of Tenochtitlan, the Aztec city constructed between the 14th and the 15th century, partially destroyed and buried after the Spanish Conquest, is located in the Historical Center of Mexico City. Because of its geological setting in the center of the Trans-Mexican Volcanic Belt, the city was built mainly from volcanic stones. Systematic excavations in the site have been carried on since late 1970s and the extreme pollution of the metropolitan area, the subtropical climate, hydrological conditions, and frequent seismic activity of the region, have accelerated degradation process of the stone structures exposed. In this paper, different aspects of weathering and stone deterioration of the Edificio B "Altar de cráneos", a remarkable structure because of the carved stones in its facades and the variety of lithic material types, are discussed. Geochemical characterization by XRF onsite, ICP-MS, ICP-OES, XRD SEM/EDS, salts identification; petrophysical properties investigated by means of thermographic analysis and previous studies of density, porosity, pore radii distribution and environmental data supported the diagnosis. A relationship, between lithic varieties, water transport properties, swelling, shrinking pressure, salt crystallization, specific weathering forms, orientation and previous conservation treatments was deduced. The obtained results help in the understanding of the different weathering process to support adequate conservation methods and materials.

Keywords: stone weathering, petrophysical properties, environmental conditions

1. Introduction

The ceremonial precinct of the Postclassical Aztec city, Mexico-Tenochtitlan, now Templo Mayor Archaeological Site, is located in the Historical Center of Mexico City which was declared by UNESCO a World Heritage Site in 1987. The site was named after the 'Great Temple' a pyramid with 100-80 meters at its base and according to the historical records, approximately 45 meters high, with two sanctuaries on top dedicated to Huitzilopochtli,

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god of war and Tlaloc, god of rain and agriculture. Archaeological studies point that it was first built as an earthen and wooden structure, when the city was founded in 1325, and enlarged six times, a common practice in pre-Columbian architecture by which buildings were periodically modified, according on political changes and ceremonial traditions (Matos Moctezuma 2014). The precinct of Tenochtitlan was destroyed after the Spanish Conquest in 1521, and remained buried until the second half of the 20th century. Although some archaeological surveys were conducted at the end of the 19th century and early 20th century, the systematic excavations at the site began in 1978 with the fortuitous discovery of the monolith of the deity Coyolxauhqui.

The Edificio B, a rectangular platform of approximately 7.8 meters E-W, 5.48 meters N-S, and 2.4 meters high, with a distinctive decoration of carved skulls in its façades, was excavated in the early 1980s (Fig. 1). Because of its location at the Northwest side of the Great Temple and its decoration, the Edificio B has been interpreted as representative of the *Mictlampa*, the land of the dead in the Mexican cosmovision. The construction presents different stages, the last one being temporarily associated with the sixth construction stage of the Templo Mayor, during the ruling of the *tlatoani* Ahuízotl (1486-1502 AD; Matos Moctezuma 2003).

Fig. 1: Edificio B, Templo Mayor Archaeological Site.

As a result of more than three decades of exposure to environmental conditions of Mexico City, different weathering effects are visible in the Edificio B. In alteration processes Geochemical and petrophysical properties of the stones, interaction within constituent materials, and the building orientation have played a crucial role in the alteration processes.

2. Properties of building materials

The main building materials used in Templo Mayor Architecture were *tezontle*, an extrusive volcanic basaltic andesite scoria, basalt, andesite, limestone, adobe, wood, and lime mortar (López Luján *et al.*, 2003). *Tezontle* was also the main building stone used in the Edificio B, the core, the blocks of the walls, the staircase that leads to the top of the structure, and most of the carvings were made of it. Macroscopically its voids are predominantly 10 millimetres in diameter, microscopically the walls of the cellular rock fabric show acicular plagioclase crystals and isolated pyroxene and amphibole crystals. Geochemically it contains approximately 60% SiO_2, 12% Al_20_3, 8% MgO, 5% Fe_2O_3, 4% CaO and 3% Na_2O. Petrophysical properties reported for this material are 35 to 66% porosity in nonweathered conditions due to its heterogeneous cellular structure, very low bulk density (1.4 g/cm^3), no measurable hydric swelling but a relatively high thermal dilatation coefficient ($7.0\times10^{-6}\ K^{-1}$), and compressive strength ranges from 12 to 32 N/mm^2 under dry conditions (Acevedo-Dávila *et al.*, 2007, Wedekind *et al.*, 2011).

Tuff stones were also used in the carvings, mostly in the North façade, and rarely basalt. The variety of pyroxene andesite tuffs of intermediate composition and dacite tuffs of acid composition show high hydric swelling and thermal dilatation coefficients that increase in weathered surfaces. Through petrographic observation and XRD, SEM/EDS analysis it was possible to characterise alteration of feldspars and some degradation products.

The Edificio B was originally covered with lime render, which is better conserved in the South façade where carvings still show several layers with traces of polychrome decoration. The loss of this finish that protected the stone from weathering is higher in the North façade. In addition, the loss of architectural elements and irregular excavation in the inside part of the structure favour water accumulation.

3. Weathering and stone decay

3.1. Environmental conditions

Systematic excavations in Templo Mayor during the 1980s suddenly exposed the structures to a highly polluted atmosphere. In the mid-1970s Mexico City was considered one of the most polluted cities of the world, and at the end of the 1980s emissions exceeded the recommendations contained in the Air Quality Guidelines of the World Health Organization (WHO). Even though a significant reduction of pollution levels has been achieved since 1990, when environmental pollution control policies were implemented, current levels of sulphates, nitrate, carbon monoxide, pollutant particulates, and ozone in México City metropolitan area, remain high. Mexico City has a temperate highland tropical climate with dry winters and summer rains. Downtown area average annual temperature varies from 12 to 18ºC, with total annual rainfall between 600 and 950 millimetres. This area exhibits the urban heat island phenomenon (UHI), induced by the concentration of ozone and aerosol particles, transported by the main wind flows that follow a north-south direction. Wet deposits in downtown Mexico City are predominantly acide (pH = 5-6.4), total deposition of the most abundant anions in the last two years reached 5.93 g/m^2 for sulphates, followed by a deposition of 4.85 g/m^2 of nitrates and 0.97 g/m^2 of chlorides (Secretaría del Medio Ambiente, 2015).

It is well known that areas that remain wet for long periods promote adhesion of particles. Deposition of transition metal oxides particles promotes oxidation reactions and favours the adhesion of pollutants that once fixed in the surface react with moisture and acid rain. The presence of sulphates and nitrates in regions of high humidity increases the solubility of metals and their potential reaction (McAlister *et al.*, 2008). These conditions also generate nucleation areas with predominant growth of sulphates that show particularly aggressive crystallization (Charola and Ware 2002, Sabbioni 2003, Charola *et al.*, 2007, Graue *et al.*, 2013, Wiese *et al.*, 2013).

In addition, ground subsidence that affects Mexico City as the result of the decreasing underground aquifer water level and the behaviour of the highly compressible lake basin sediments (compression index up to 10, with water content up to 400%, and plasticity index over 300%), has led to a rate of -92 to -115 millimetres per year (Cabral Cano *et al.*, 2011), causing severe structural problems in buildings. Subsidence has caused an inclination of 4 degrees north of the Edificio B, and consequently, compressive stress on the North façade of the building has produced cracks. Inclination also reduces insolation which slows water evaporation and contributes to the accumulation of polluting particles in the lower zone. Moreover, constant seismic activity increases significantly structural stress, considering that waves are accelerated and amplified in lacustrine soils (Díaz Rodríguez 2006).

3.2. Weathering effects on stone materials

Weathering effects observed on the façades of the Edificio B are the result of complex decay phenomena that affect volcanic stones by different mechanisms. As a result of the environmental exposure, tuff stones are less preserved than vesicular basalts or *tezontle* that shows significant resistance to weathering. Interaction of pollutants with stone materials is higher on the North façade due to the direction of prevailing winds and low insolation that leads to high humidity conditions. In this façade only 18% of lime renders are preserved, 12% of the surface remained wet by October when rainy season was already over, and 9% showed contour scaling, weathering form frequently associated with salt efflorescence. In the East façade lime renders are preserved on 20% of the surface, while the areas affected by weathering processes represent less than 1%. The South facade shows the best condition, 51% of the surface preserve lime renders and remains of polychrome decoration, only 0.3% of the surface is affected by weathering processes (Fig. 2).

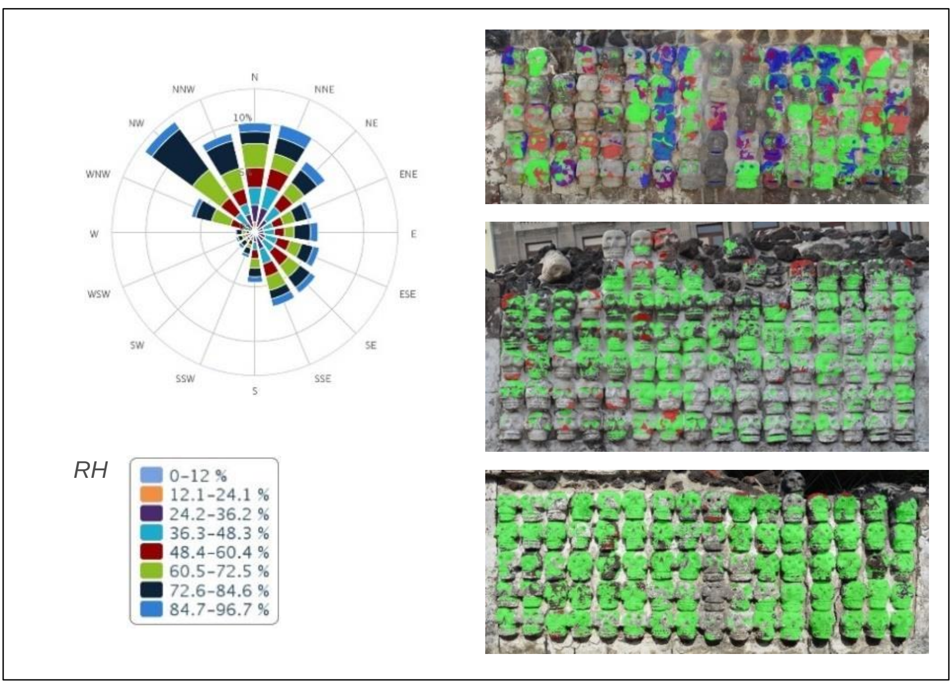

Fig. 2: RH values according to the direction of prevailing winds, weathering (red), wet areas (blue), and lime renders preserved (green), on the North, East and South façades.

Exposure and critical property values as thermal dilatation, hydric swelling, anisotropic behaviour or compressive strength, as well as cementation also define building stones resistance to weathering and weathering forms (Wedekind *et al.*, 2011). Within tuff stones while exposure to wet-dry conditions increases weathering effects by salts crystallization and erosion, prolonged wetness accelerates decay by the presence of soluble salts and pollutants that promotes an acidic medium causing the chemical decomposition of feldspars and oxidation. On the other hand, ion migration by dissociation of alkaline components of mortars and the dragging of calcite particles promote concentration of high *pH* solutions into the tuff stones pores. These alkaline mediums are particularly aggressive for acidic tuffs causing the dissolution of silica and plagioclase.

Hygroscopic behaviour significantly determines the resistance of building stones to weathering conditions because it prevents or promotes water, soluble salts and contaminants transport, leading to the mentioned degradation mechanisms. Such behaviour is controlled by the amount of swelling clay minerals and the size and distribution of active capillary pores (micropores of 0.1 to > 100 µm) (Ruedrich *et al.*, 2011, López-Doncel *et al.*, 2013, Wedekind *et al.*, 2013). The concentration of capillary pores in the weathered zones of stones increases and thus the penetration and retention of water, while hardness decreases. Therefore, interaction between materials with marked differences in thermal and hygroscopic behaviour accelerates decay of the more hygroscopic and less resistant ones, as can be observed in tuffs surrounded by vesicular basalts in the North façade, under prolonged wetness conditions. Through thermographic analysis it was possible to confirm that the loss of lime render finish increases significantly differential thermal stress in the most exposed carvings (Fig. 3).

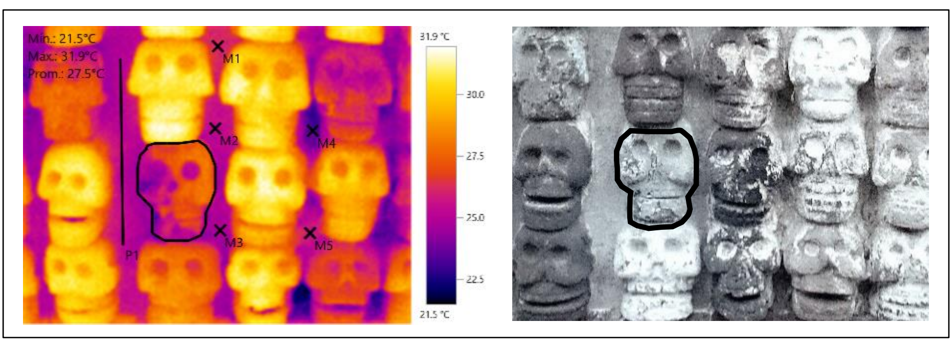

Fig. 3: Thermal image showing differences in lime mortar junctions, tuff and basalt carvings behaviour.

Since erosive process affects dacitic and andesitic tuffs in the East façade, scaling, detachment and disintegration are the weathering forms observed on similar varieties in the North façade. Poor welded andesitic tuffs in the North façade are highly affected by salt crystallization which causes granular disintegration of the matrix, hornblende phenocrysts loss and the consequent collapse of the surrounding material. Instead pyroxene dacitic tuffs in the North façade show a typical weathering form starting with crust formation and scaling approximately 0.5 cm from the surface, combined with back-weathering, microcracks and salt crystallization (Fig. 4a/I). In contrast same type of tuff stones in the East façade shows erosive weathering effects like sanding (Fig. 4b/II).

On the other hand, *tezontle* shows significant resistance to both wet-dry conditions and prolonged wetness because it almost does not show hydric swelling due to the fact that linked pore space areas are sporadic within the material. Nevertheless, microscopically alteration processes of the plagioclase in the rock fabric cell walls could be observed, as well as salt crystallization on the surface. Macroscopically the most common deterioration observed in this volcanic rock type is due to fractures and cracks because of its moderate hardness and high thermal dilatation (Fig. 4c/III).

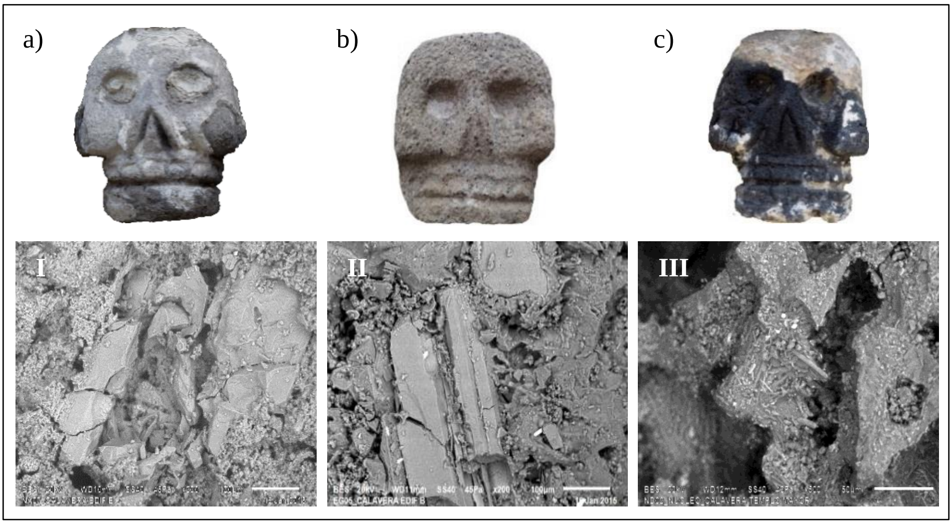

Fig. 4: Different weathering effects macroscopically and microscopically. SEM images; a/I) dacitic tuff skull in the North façade (200×100 µm); b/II) dacitic tuff skull in the East façade (200×100 µm); c/III) tezontle skull in the North façade (500×50 µm).

4. Previous treatments and future perspectives

Some materials used in previous conservation treatments in the Edificio B, have proven to have long-term negative effects, particularly the application of consolidating and water-repellent products during the 1980s and 1990s, such as Curasol, Mowilith DM4, Primal AC33, Wacker 19OL, among others (Matos Moctezuma 1993, Franco Brizuela 1990). Some negative effects of these products are related with their limited penetration and surface hardening, which has reduced the evaporation and solutions transfer capacity of the stones, favouring salts cryptocrystallization and detachment of the hardened layers.

Future interventions should consider that conservation of the structure will not be achieved through isolated treatments applied on the building materials. For instance, it is a priority to stop the transport of water salts and contaminants into the structure, a challenging task taking into account the environmental and underground conditions. Solutions should look up for balancing the system attending structural and water conduction problems, as well as reducing the negative effects of building materials interaction and exposure, considering differences in their proprieties and condition.

5. Conclusions

The exposure conditions and the distribution of building materials in the Edificio B has led to the accelerated decay of the North facade. In the alteration process a relationship between lithic varieties properties such as water transport, hydric swelling, shrinking pressure, thermal dilatation, and specific weathering forms, can be deduced. In addition to the intrinsic properties of the materials, exposure and previous conservation treatments play an important role in accelerating the deterioration processes. The obtained results help in the understanding of the different factors involved in the weathering process and to recommend conservation methods and materials. To slowdown deterioration of building stones in challenging environments such as Templo Mayor Archaeological Site, a multifactorial and interdisciplinary approach to conservation problems is needed considering that structures are dynamic systems that require constant evaluation of their response to changing environmental conditions.

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