Mapping Atmospheric Corrosion as a Heritage Management Tool in Oaxaca, Mexico

Mapeando a Corrosão Atmosférica como Ferramenta de Gerenciamento de Patrimônios em Oaxaca, México

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Abstract: Archaeometry is the application of Natural Sciences techniques, including Geography, to solve problems in Archaeology and Heritage Conservation. Corrosion constitutes the main deterioration process of metals, which is triggered by the properties of the surrounding matrix. This work focuses on atmospheric corrosion in Oaxaca, Mexico. Methods used included the creation of atmospheric corrosion stations where weight loss was measured and geo-localization of archaeo-metallurgical heritage was determined in the study area. A brief historical review of the cultural importance of metals in Mexico is also treated. Results for the three first months of measurement showed that atmospheric corrosion values are higher in the city centre, where heritage is more concentrated. Air pollution and increased temperatures attributed to global warming are considered to be relevant for explaining the data obtained. Further analysis of a full year cycle is expected to reinforce this argument. The methods used are shown to be useful heritage and urban management tools applicable to other geographic spaces.

Keywords: Archaeometry; Heritage Conservation; Atmospheric Corrosion; Archaeometallurgy; Global Warming.

Resumo: Arqueometria é a aplicação de técnicas em Ciências Naturais, incluindo a Geografia, para resolver problemas de Arqueologia e Conservação do Patrimônio. A corrosão constitui o principal processo de deterioração dos metais, desencadeado pelas propriedades da matriz circundante. Este trabalho enfoca a corrosão atmosférica em Oaxaca,

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México. Os métodos incluem a criação de estações de corrosão atmosférica para a técnica de perda de peso e a geolocalização do patrimônio arqueometalúrgico na área estudada. Uma breve revisão histórica da importância cultural dos metais no México também está incluída. Os resultados dos três primeiros meses de medição mostram que os valores de corrosão atmosférica são mais altos no centro da cidade, onde o patrimônio é mais concentrado. A poluição do ar e o aumento da temperatura atribuídos ao aquecimento global podem ser relevantes para explicar os dados obtidos. Uma análise mais aprofundada de um ciclo completo do ano pode reforçar essa tendência. O método mostrado se torna uma ferramenta útil de gestão patrimonial e urbana e é aplicável a outros espaços geográficos.

Palavras-chave: Arqueometria; Conservação do Patrimônio; Corrosão Atmosférica; Arqueometalurgia; Aquecimento Global.

Introduction

In the widest sense, Archaeometry is the use of techniques proper of the Natural Sciences, Geography included, in order to solve problems in both, Archaeology and Heritage Conservation (ARTIOLI, ANGELINI, 2010; CHURCH, BRANDON, BURGETT, 1999). Heritage Conservation constitutes a complex field whose goals imply multidisciplinary cooperation. The origin of this work rose from the need to assess atmospheric corrosion in order to preserve archaeometallurgical heritage in Mexico. Such heritage category includes any material culture built in metals (ROBERTS, THORNTON, 2014). Corrosion becomes the main deterioration process of metals exposed to the atmosphere and it depends on conditions such as relative humidity, temperature and presence of aggressive chemical species (LEYGRAF et al., 2016). Since these values vary constantly, updates are continuously required, yet in many places, these measurements remain undone.

Atmospheric corrosion stations for heritage conservation purposes can rely, among others, on temperature and relative humidity measures through time, becoming archaeometric in nature by sharing equipment and techniques usually applied in Climatology. Besides, the concept of station links to a specific site and therefore, the study of atmospheric corrosion demands some sort of spatial analysis to yield results. The presence or absence of aggressive chemical species might relate to natural and/or anthropogenic processes. A great portion of archaometallurgical heritage assets are located in cities and therefore, air pollution can be linked to human activity, adding the social and urban components the the analysis.

In order to establish the relevance of the topic, this work comprises brief reflections about the historic and archaeological importance of archaeometallurgical heritage in the American Continent and specifically in Mexico, where the research is developed. Mentions to natural causes in atmospheric corrosion increase, such as volcanism in central Mexico, also appear. However, the main objective of this work was to characterize the corrosive properties of the atmosphere in Oaxaca City, seat to a relevant cultural heritage set, in order to identify differences in the geographical space. The study case

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shows the consequences of anthropogenic activity, especially in the city centre where heritage concentrates.

Shown data correspond to the analysis of the first three months of measurement from a full year experiment. Still, preliminary analysis shows a tendency towards temperature increase, presumably related to global warming. As temperature rises, so will corrosion and the consequent loss of cultural heritage and infrastructure in general. Economic loss due to corrosion can represent around 5% of the Gross Domestic Product in a given country (BIEZMA, SAN CRISTÓBAL, 2005). In the case of heritage loss, there can be no quantification because of its unique nature.

Considerations About Archaeometallurgical Heritage in Mexico

During the 19th century, Archaeology relied on chronologies in order to explain the human past. Some of such proposals relied on technological aspects of material culture. This way, social sciences proposed consecutive development phases such as savagery, barbarism and civilisation, which became accepted categories in those times. Within such a theoretical context, Christian Jurgensen Thomsen, curator at the precursor of the Danish National Museum, proposed in 1836 the Three Ages system (Stone, Bronze, Iron) in order to study Nordic Prehistory. Later archaeological findings by Worsaae seemed to support Thomsen's model (HEIZER, 1962: 259). Nowadays, single-track evolution social models result obsolete. Still, it is possible to highlight the relevance of metallurgy regarding possible technologies for a given human group, both diachronically and synchronically. This is why Archaeometallurgy, the study and conservation of metallic artefacts, has become a relevant sub-field both for Archaeology and for Heritage Conservation.

As in other areas of the world, in the case of the American Continent, metallurgy started using native metals such as gold, silver, copper and their alloys (PATTERSON, 1971). The Great Lakes cultural area in the current countries of Canada and United States was the cradle for a metallurgical tradition known as Old Copper, which eventually spread all through North America. In turn, the Andean region witnessed the rise of a highly sophisticated metallurgical technology based on gold, silver and diverse alloys. Metallurgy reached Mesoamerica in current Mexico in relatively late times, yet this happened when the techniques and results were already of higher quality (LARA, 2006: 3-5). In the case of Mexico, the treasure found in an ancient tomb in Monte Albán, Oaxaca, represents a worldwide known example of metallurgical dexterity (CAMACHO-BRAGADO et al., 2005).

European colonisation during the 16th century and further, implied the gradual introduction of iron and bronze technologies into the American Continent. In the specific case of Mexico, another relevant issue was the foundation of mining sites, fact that implied a major geographic transformation, since it became one of the main axes of colonial society (SEMO, 1973). In terms of heritage, metallurgy-related sites such as the Historic Town of Guanajuato and Adjacent Mines or even complex routes like the Camino Real de Tierra Adentro are currently included in the UNESCO World Heritage List. A further sociocultural transformation relates to the Industrial Revolution, which

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reached the country during the late 19th and early 20th centuries (HABER, 1992). In this case, the introduction of the railway and the steel technology once again relate to metallurgical aspects (ORTIZ-HERNÁN, 1987). In the worldwide postmodern present, new metals and alloys play a key role in avant-garde processes such as space exploration and cyber-technology.

As result of the historic events explained above, in Mexico, archaeometallurgical heritage includes a vast array of artefacts and architectural structures comprising a long time sequence. Some of the most conspicuous examples in urban landscapes include historic bells, sculptures, and buildings. However, even small artefacts like coins or archaeological pieces in a museum form part of this heritage subset. It is worth mentioning that heritage conservation constitutes a relevant field in Mexico because the country ranks first in the American Continent and seventh worldwide in terms of sites included in UNESCO's World Heritage List. In fact, due in part to cultural tourism, Mexico stands out as a tourist power, being the sixth most visited country in the world (WORLD TOURISM ORGANIZATION, 2018).

Geography, Athmospheric Corrosion and Cultural Heritage in Mexico

Corrosion constitutes the deterioration of metals due to the action of aggressive chemical species, which alter the original crystalline arrangement. It is an electrochemical process and its velocity rate depends on temperature, relative humidity and presence of pollutants (STANSBURY, 2000; FONTANA, 2005; REVIE, 2008). Metallic cultural artefacts or structures appear on aquatic, subterranean or atmospheric contexts, the last mentioned possibility addressed in this work. Sodium chloride (NaCl), abundant in coastal environments, and sulphur dioxide (SO2), a common fossil combustion sub-product, are two of the most aggressive chemical species affecting metals, however many other agents also have corrosive properties (LEYGRAF et al., 2016). Major works assessed atmospheric characterisation, including the generation of corrosion maps (MORCILLO et al., 1998), even so, due to the constant atmospheric change, new measurements are continually required in order to update the existing information. Changes in atmospheric corrosion properties obey both, natural (climate change, natural disasters) and anthropogenic factors such as urban growth, industrial activity, and pollution in its broadest sense.

Volcanic activity implies gas emission rich in sulphur compounds, as well as the expulsion of other materials, which can cause metallic corrosion. A number of researches address these interactions from a natural hazards point of view (OZE et al., 2014) or from a strict corrosion approach (WATANABE et al., 2006). These kinds of works do not attend heritage conservation views, which imply specifis needs. Indeed, there exist many other valuable works regarding atmospheric corrosion of cultural metals (BERNARD, 2009; DILLMAN et al., 2013) and some of them stress the importance of long-term prediction (DILLMAN et al., 2014). Still, the relationship between rapid change in atmospheric corrosion and heritage conservation remains as a relatively unexplored research field.

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In Mexico, our interest about the relationship between atmospheric corrosion and archaeometallurgical heritage started in relation to volcanism and now extends to other contexts. Located in the southern portion of North America, Mexico has a complex tectonic system. Most seismic and volcanic activity in the country relates to the subduction of Cocos Plate under the North American Plate, creating a trench corresponding to a great portion of the Mexican Pacific coast. Elsewhere in the world, subduction produces not only earthquakes but also a volcanic chain parallel to the trench, and therefore, coastal. In the case of Mexico, horizontal subduction causes alignment of volcanoes in a different angle, appearing well into the continent. At the same time, the direct relationship between subduction and volcanism represents ongoing research (VERMA, 2002; PÉREZ-CAMPOS, 2008). In any case, the Popocatépetl volcano is one of the most active ones in the country. The summit of this stratovolcano divides three states: Morelos, Puebla and Mexico State, in the centre of the country and south to the capital city. One of them, Morelos State, is fully comprised of the Balsas River Basin, which drains into the Pacific Ocean.

During an industrial archaeology research (HERNÁNDEZ-ESCAMPA, 2006), X-ray diffraction technique characterised the corrosion products on steel railway bridges in Barranca Honda, Morelos. Results showed the presence of usual oxides, all of them expected in a pristine rural atmosphere, as it was the case, except a compound known as melanterite ($FESO4 \cdot 7H2O$). The finding became relevant because there is no possible sulphur source in the context other than the Popocatépetl volcano, located about 80 km away from the studied site. It is important to highlight that melanterite is an unstable compound and it decomposes rapidly. The clear presence of the compound implies a constant or at least intermittent source of sulphur compounds, presumably volcanic SO2.

Morelos State is the seat for a number of 16th century monasteries. These architectural complexes together with others in the neighbouring Puebla State have been included in the UNESCO World Heritage List. Actually, the whole asset's name is "Earliest 16th century Monasteries on the Slopes of Popocatépetl" which is enough to illustrate the geographical proximity of the monasteries to the aggressive species' source. Even when these and other relevant structures are made of stone, they still include metallic components such as historic bells or clocks that are prone to corrosion under the described circumstances (Figure 1). Needless to say that not only the monasteries or their metallic components but also all the archaeometallurgical heritage within the volcanic influence range might be in different levels of exposure to the corrosive gases. This experience rose the interest towards more detailed atmospheric monitoring in terms of heritage conservation and the need to expand the analysis to other relevant cultural sites near the volcano. Besides natural processes such as volcanism in central Mexico, other pollution sources and their mechanisms become study cases, as is the case of this work.

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Figure 1 – The Hernán Cortés Palace in Cuernavaca, the capital city of Morelos State, was built during the 16th century. Mainly made of stone, it lodges a clock tower, which forms part of the city's archaeometallurgical heritage. In the picture, the building was restored after the 7.1 magnitude earthquake that took place in 2017.
Source: the authors.

Atmospheric Corrosion Measurements in Oaxaca City, Mexico

Once established that the corrosive properties of the atmospheric matrix constantly vary in time, the need for updated measurements in real time becomes clear. The city of Oaxaca, capital of the homonymous Pacific coastal Mexican state, forms part of the UNESCO's World Heritage List. In this case, both the remarkable colonial city centre and the nearby archaeological site of Monte Albán constitute the reasons for inclusion. No updated archaeometallurgical catalogue currently exists for the historic city. Therefore, ongoing research includes the creation of three catalogues: historic bells, sculptures and 20th century architectural structures (Figure 2). These efforts constitute an initial approach since detailed works are also required for items such as metallic fences, handrails, and other small artefacts. A second strategy implies the creation of atmospheric corrosion stations in the city. The aim of the project, started during the spring season 2018, was to establish the current atmospheric corrosion properties in terms of heritage conservation. Oaxaca State is located in the Cocos Plate subduction zone and therefore the region is prone to intense seismic activity and tsunamis (SUÁREZ, ALBINI, 2009), however, there

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is no current volcanic activity due to the displacement of the volcanic chain explained above. On the other hand, the city has increased its vehicle numbers more than 5 times in the last 30 years (INSTITUTO NACIONAL DE GEOGRAFÍA Y ESTADÍSTICA, 2018); this situation justifies the current research because anthropogenic activity, as well as climate change, might provoke an increase in atmospheric corrosion as pollution and temperature rise.

Figure 2 – Macedonio Alcalá Theatre in Oaxaca is an illustrative example of early 20th century architecture with metallic structural and ornamental elements.
Source: the authors.

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In order to fulfil such a goal, and following accepted procedures in Materials Science (ASTM, 1999), atmospheric corrosion measurements were quantified in five stations. The first one was located in the historic centre near Santo Domingo convent, a cultural icon of the city. The other four stations were located in the cardinal points with respect to the central station. Figure 3 shows the exact location of the stations, the extent of Oaxaca City within its own territory and neighbour municipalities, all heavily urbanised. Stations requirde a safe place for their installation because, unfortunately, metallic plaques can be lost if placed in public spaces. This fact determined their exact location. It is worth mentioning that a standard complete atmospheric corrosion measure should last a year. This way, the assessment includes yearly variations of temperature and relative humidity. Even so, partial measures can give some clues about the corrosion process for heritage conservation purposes. The main technique reported here refers to plaque weight loss.

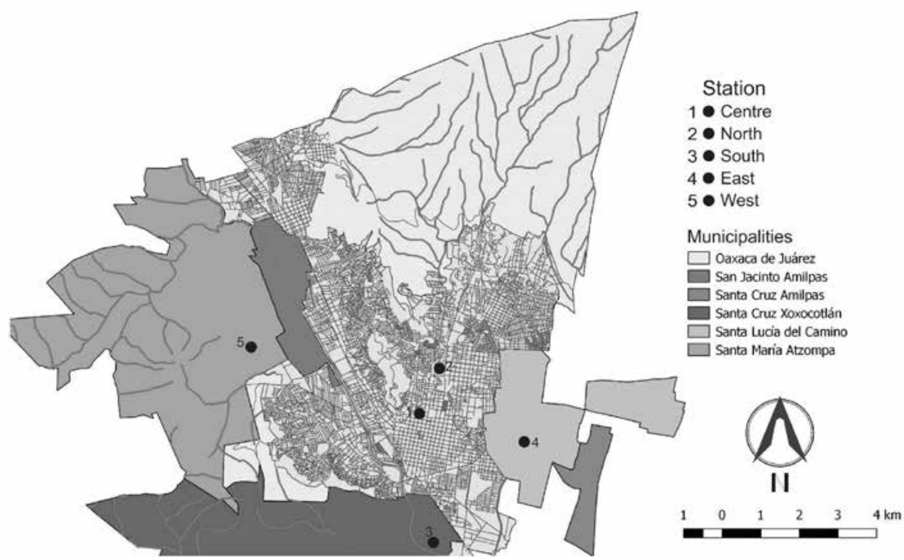

Figure 3 – Oaxaca City and neighbour urban municipalities map showing the location of the atmospheric corrosion stations.
Source: the authors.

The weight loss technique consists of exposing standardised metallic plaques (10 x 15 cm) to the atmosphere during a time lapse. Original mass of each plaque is recorded and compared to its final mass. Each measure includes the average result of at least two identical plaques. Corrosion products formation theoretically produces core metal loss. However, especially in initial or short terms, the corrosion products might adhere to the surface producing a false weight increase. The metallic composition should also be considered because ferrous metals usually produce not adherent corrosion products while copper and its alloys such as bronze or brass might produce a patina, understood as a highly adherent and protective layer. The corrosion rate is calculated using the following equation:

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where: Vcorr = corrosion rate (mm/year); mi = initial mass(mg); mf = final mass (mg); ρ = material density (mg/mm3); A = exposed material surface (mm2); t = time (year).

In this work, two different metals were chosen, exemplifying cultural relevant metallic families. Iron plaques are intended to represent not only iron but also give some clue about the atmospheric behaviour of other ferrous materials such as steel. In turn, the election of copper might hint the processes of copper itself, bronzes and brass. Relative humidity and temperature were also measured using a HOBO equipment in order to eventually correlate these variables with corrosion rate. As explained above, copper and its alloys represent a culturally relevant group of metals represented since Prehispanic times in the studied contexts. Ferrous materials represented by Iron relate to more recent cultural processes. It is woth mentioning that corrosion measurements can also include zinc or aluminum plaques, or else, according to the interests of the research.

Table 1 shows the temperatures measured at the five atmospheric corrosion stations. Results are compared to the annual average temperature from 1951 to 2010 provided by CONAGUA (Comisión Nacional del Agua, Water National Commission), the official government agency in charge of water and climate issues in Mexico. Values shown for each station correspond to a three-months period starting on March 21st, 2018. As it can be seen, all data are higher than their average reference number. Spring tends to be the hottest season of the year in Oaxaca's region, but even so, the full year analysis might support this rising temperature tendency. Since higher temperatures relate to faster corrosion rates, this is a relevant variable for this kind of research.

Table 1 – Temperatures measeured at the atmospheric corrosion stations

TEMPERATURE			
STATION	**MIN. TEMP** °C	**MAX. TEMP** °C	**MEDIUM TEMP** °C
ANNUAL AVERAGE TEMPERATURE 1951-2010	13.2	29.3	21.3
CITY CENTRE	20.92641	28.05117	24.09344
NORTH	18.02514	28.56552	22.89562
SOUTH	26.03779	32.03821	28.64649
EAST	21.20851	33.772	26.25748
WEST	16.9869	36.763	25.1368

Source: the authors

Relative humidity results measured during the same period showed that the higher values correspond to the North station with a 55.7% average, while the lowest cypher

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corresponds to the South station with 44.8%. In this sense, the Centre station showed an intermediate value of 50.05%. Higher corrosion rates should occur as relative humidity increases. However, neither the temperatures nor the relative humidity data showed this tendency, as it will be further explained.

Table 2 summarises the corrosion rate results for all the stations for both iron and copper. In the case of iron, the highest corrosion rate corresponds to the historic centre. As the value corresponds to a higher decade of magnitude, this implies that the corrosion of iron is happening ten times faster than in other stations or even one hundred times faster if compared to the south. This happens despite that the centre location is neither the hottest nor the most humid one as already discussed. The result implies that aggressive chemical species must be present in higher concentrations in that context. In the case of copper, results show comparable values in the same decade, for all stations, the higher values in the north station, also affected by traffic collapse.

Table 2 – Corrosion rates obtained in the atmospheric corrosion stations.

CORROSION RATE mm/year		
STATION	Fe	Cu
	Iron	Copper
CITY CENTRE	**0.0029955889 (highest value involved)**	0.000160682
NORTH	0.0003430064	0.000385637
SOUTH	0.0000686013	0.000174072
EAST	0.0001919259	0.000191926
WEST	0.0002120112	0.000212011

Source: the authors

Table 3 shows the geolocalization of early 20th century architecture in Oaxaca obtained by GPS. All of the catalogued structures are located within the historic centre or immediately nearby, especially to the north in a section called Reforma, created precisely during that period. North station was located in this area in order to assess atmospheric corrosion in this area of interest. Other catalogs, referring to bells or smaller items are still in process. However, the pattern is similar: concentration in the city centre.

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Table 3 – Geolocalization of early 20th century architecture in Oaxaca. Proper names in Spanish. Name of architect or institutions involved in building are also included.

Building		Architect/Institution	N	W
1	Estadio de béisbol “Eduardo Vasconcelos”	Luis Álvarez Varela	17.070022°	-96.713307°
2	Hotel Victoria	Salvador Martín del Campo	17.073119°	-96.729350°
3	Templo de la virgen de los Pobres	Luis Lobato Manjarrez	17.077406°	-96.712491°
4	Escuela Preparatoria Gral. UABJO	Enrique de Esesarte	17.068856°	-96.714005°
5	IMSS	IMSS	17.072158°	-96.720979°
6	Mercado del Ex marquesado	Enrique de Esesarte	17.063883°	-96.731570°
7	Gasolinera San Pablo	Alejandro Reyna Romero	17.061283°	-96.722188°
8	Jardín de Niños “Esperanza López Mateos”	Octavio Flores Aguillón	17.054282°	-96.726867°
9	Escuela España	Enrique de Esesarte	17.073569°	-96.715950°
10	Hospital Dr. Aurelio Valdivieso	Alberto Castro Montiel	17.081844°	-96.718530°
11	Edif. Multifamiliar Sta. Elena	Enrique de Esesarte	17.070161°	-96.721172°
12	Edif. Multifamiliar el Carmen	Enrique de Esesarte	17.067950°	-96.720310°
13	Hotel Señorial	Enrique de Esesarte	17.060489°	-96.726070°
14	Capilla monjas de la santa cruz	Enrique de Esesarte	17.071667°	-96.716895°
15	Hospital Pdte. Juárez	ISSSTE	17.084042°	-96.722738°
16	Central de autobuses de segunda	Celestino Gómez S.	17.060456°	-96.736084°
17	Templo iglesia de cristo	Rafael Ballesteros	17.070333°	-96.714927°
18	Auditorio Guelaguetza	Mario del Olmo	17.068647°	-96.730720°
19	Hotel Misión de los Ángeles	Enrique de Esesarte (Remodelación)	17.072584°	-96.719239°
20	D.O.I.A.	CAPFCE	17.048269°	-96.712508°
21	Planetario Nundehui	Rafael Ballesteros	17.072535°	-96.732781°

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	Building	Architect/Institution	N	W
22	Fábrica CIMAPLAS	Javier Avendaño Bautista	17.047783°	-96.638901°
23	Cinema Ariel 2000	Enrique de Esesarte	17.067075°	-96.720516°
24	Cámara de diputados	Antonio Melgoza Castillo	17.068303°	-96.720257°
25	Centro cultural Oaxaca	Bulmaro Guzmán y Fdo. Rmz	17.079750°	-96.742258°
26	Cinema Géminis	Enrique de Esesarte	17.078706°	-96.715066°
27	Hotel Fortín plaza	Rafael Ballesteros	17.073669°	-96.727234°
28	Casa-Clínica Jorge Villar	Enrique Núñez Banuet	17.074247°	-96.717208°
29	Cámara Mexicana de industria de la construcción	José Luis Fabila	17.093369°	-96.712784°
30	Casa para ancianos "Los Tamayo"	Abraham Zabludovsky	17.066561°	-96.727810°
31	Plaza Santo domingo	José Manuel Arnaud Viñas	17.065367°	-96.724008°
32	Almacén "el corte"	Enrique Núñez Banuet	17.078850°	-96.716190°
33	U.R.S.E. campus Rosario	Joaquín Calderón Contreras	17.049200°	-96.693279°
34	Salón de fiestas "Dionysus"	Enrique de Esesarte	17.066981°	-96.701860°
35	Sears Plaza del Valle	Salomón Rojas Aceval	17.038778°	-96.711675°
36	Gimnasio de la U.A.B.J.O.	Luis Enrique Martínez	17.047314°	-96.714809°
37	Edificio "DEKORA"	Álvaro Herrera Mendoza	17.070792°	-96.715570°
38	Bar "el Pescador"	Carlos San Pedro Martínez	17.054150°	-96.727217°
39	Edificio para el G.E.O. en naranjos y Dalias	Enrique A. Calvo Y Eduardo Narváez	17.080114°	-96.711100°
40	Oficinas CFE en Etla	Alfredo Carreño León	17.205453°	-96.802830°
41	Teatro "Macedonio Alcalá"	Ing. Rodolfo Franco Larráinzar	17.061531°	-96.723500°

Source: the authors

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Figure 4 represents the city of Oaxaca and adjacent urban municipalties. Corrosion stations are located showing the corrosion values as bars. Values clearly show higher corrosion rates in the central portion of the studied area and also in the northern sector. These areas are usually collapsed by traffic because they concentrate different services in the city. At the same time, these areas also lodge the heritage assets.

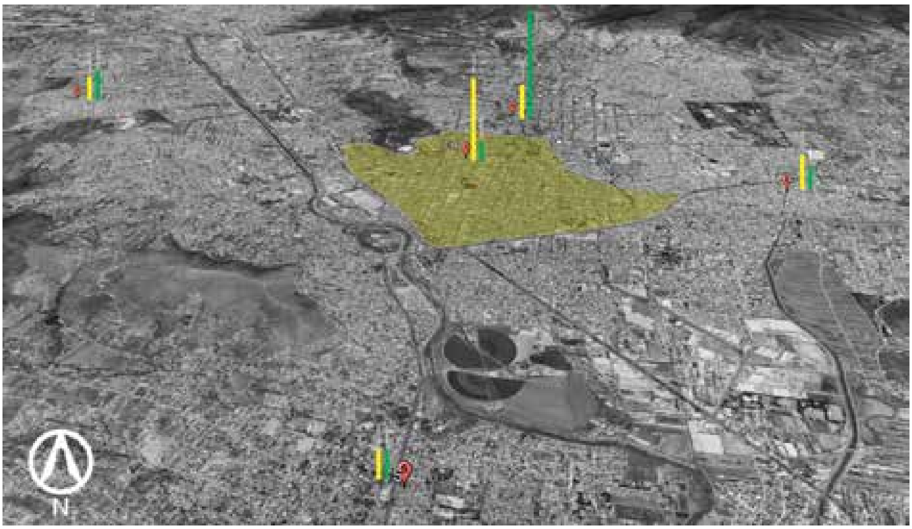

Figure 4 – Oaxaca city and conurbated area. Bars represent corrosion values for iron (yellow) and copper (green). Shaded area represents the historic centre where heritage is concentrated.
Source: the authors.

Translating all data to heritage conservation purposes, even when the values obtained in Oaxaca result relatively low, it is clear that a problem exists in the historic centre, where most of the heritage assets are located. A further step could be correlating the data and the ongoing archaeometallurgical catalogues to produce risk maps in terms of corrosion rate. Even with the existing observations, solid conclusions arise. Oaxaca is not an industrial or maritime city; therefore, most atmospheric pollutants must come from vehicles. At this point, it is important to mention that traffic collapse occurs frequently in the historic centre, which is barely pedestrian. As it has happened in other cities like Seville, Spain (Gavira Guerra, 2010), heritage deterioration due to vehicle pollution could be the starting point for urban decisions such as expanding the pedestrian zones and creating a gas emission's control program, currently inexistent in the city. Many Mexican cities have started to implement urban projects in order to reduce traffic congestion, such as the Ecozona in Cuernavaca or the River Promenade in Orizaba, but Oaxaca has not developed them yet. About the different behaviour of both metals analysed so far, cuprous artefacts show more resistance to the atmosphere in Oaxaca, while iron and

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steel show more vulnerability. Preliminary evidence shows that recent heritage such as industrial or contemporary architecture and artefacts need closer attention.

As this preliminary spatial analysis becomes more detailed, results will constitute a useful tool for heritage conservation purposes, and for urban planning decissions. A shared trait in Latin America is the rapid urban growth, accompanied by massive use of automobiles. Such a fact does not constitute a sustainable tendency. Global warming predictions ususally refer to biological or climatological consequences. Here we start to see that cultural heritage is also at risk. Even when infrastructure might support higher corrosion rates, yet at a considerable economic cost, much more delicate material culture, as heritage is, might not resist in the long term.

Conclusions

Archaeometallurgical heritage constitutes a relevant subset within material culture. Metallic artefacts are constantly interacting electrochemically with their surrounding matrix, which in many cases is atmospheric. Therefore, corrosion becomes the main deterioration process for this particular kind of heritage, linked to air pollution. In the case of the analysed areas, it is possible to determine that natural processes such as volcanism can readily increase the presence of aggressive chemical species in the atmosphere. The same situation occurs with anthropogenic activity as exemplified with fossil fuels combustion by vehicles. The atmospheric corrosion rate is not always measured in terms of heritage conservation. However, the scientific techniques yield results, which can become heritage management tools. Volcanic activity, due to its unpredictable nature, might represent major challenges in the sense of establishing regular patterns in metallic corrosion. However, its effects on materials can be assessed properly. In the case of urban development and vehicles' increase, regulations that are more effective might be established, such as creating pedestrian areas in historic cities or around heritage assets in general. In the specific case of Oaxaca, this kind of measures should appear in a nearby future in order to protect its great richness. It is expected that the methods and experiences presented in this work can be adapted to many other cases in the Latin American region since both, volcanism and urban growth, constitute shared processes throughout the entire area.

References

ARTIOLI, G.; ANGELINI, I. *Scientific methods and cultural heritage: an introduction to the application of materials science to archaeometry and conservation science*. Oxford: Oxford University Press, 2010.

ASTM G50 ASTM G1. *Preparing, Cleaning and Evaluation Corrosion Test Specimens*. ASTM, 1999.

BERNARD, M. C.; JOIRET, S. Understanding corrosion of ancient metals for the conservation of cultural heritage. *Electrochimica Acta*, v. 54, n. 22, p. 5199-5205, 2009.

DOI: 10.36403/espacoaberto.2019.28384 ISSN 2237-3071

CAMACHO-BRAGADO, G. A.; JOSÉ-YACAMAN, M.; ORTEGA-AVILES, M.; VELASCO, M.A. A microstructural study of gold treasure from Monte Alban's Tomb 7. *JOM*, v. 57, n. 7, p. 19-24, 2005.

CHURCH, T.; BRANDON, R. J.; BURGETT, G. R. GIS applications in archaeology: method in search of theory. In: WESTCOTT, K. L.; BRANDON, J. *Practical applications of GIS for archaeologists. A predictive modelling toolkit*, p. 135-155. London: Taylor & Francis, 1999.

DILLMANN, P.; WATKINSON, D.; ANGELINI, E.; ADRIAENS, A. (eds.). *Corrosion and conservation of cultural heritage metallic artefacts*. New York: Elsevier, 2013.

DILLMANN, P.; BERANGER, G.; PICCARDO, P.; MATTHIESSEN, H. *Corrosion of metallic heritage artefacts: investigation, conservation and prediction of long-term behaviour*. New York: Elsevier, 2014.

FONTANA, M.G. *Corrosion engineering*. New York: Tata McGraw-Hill Education, 2005.

GAVIRA GUERA, C. Los beneficios de la peatonalización. Sevilla: *Diario de Sevilla*, 29 November 2010.

HABER, S. *Industria y subdesarrollo: la industrialización de México, 1890-1940*. Mexico City: Alianza Editorial, 1992.

HEIZER, R. F. The Background of Thomsen's three-age system. *Technology and Culture*. v. 3, n. 3, p. 259-266, 1962.

HERNÁNDEZ-ESCAMPA, M. *El Patrimonio Ferroviario de Barranca Honda, Morelos. Arqueometría y Conservación*. Master's degree thesis. Universidad Autónoma del Estado de Morelos, 2006.

INSTITUTO NACIONAL DE GEOGRAFÍA Y ESTADÍSTICA. Vehículos de motor registrados en circulación. Mexico City, 2018.

LARA, C. La metalurgia precolombina. Técnicas y significados. *Apachita*. v. 7, p. 3-5, 2006.

LEYGRAF, C.; WALLINDER, I. O.; TIDBLAD, J.; GRAEDEL, T. *Atmospheric corrosion*. Hoboken: John Wiley & Sons, 2016.

MORCILLO, M.; ALMEIDA, E.; ROSALES, B.; URUCHURTU, J.; MARROCOS, M. Corrosión y Protección de Metales en las Atmósferas de Iberoamérica. "*Parte I: Mapas de Iberoamérica de Corrosividad Atmosférica (Proyecto MICAT)*". Programa CYTED, 1998.

ORTIZ-HERNÁN, S. *Los ferrocarriles de México, una visión social y económica, I. La luz de la locomotora*. Mexico City: Ferrocarriles Nacionales de México, 1987.

ISSN 2237-3071 DOI: 10.36403/espacoaberto.2019.28384

OZE, C.; COLE, J.; SCOTT, A.; WILSON, T.; WILSON, G.; GAW, S.; LI, Z. Corrosion of metal roof materials related to volcanic ash interactions. *Natural Hazards*, v. 71, n. 1, p. 785-802, 2014.

PATTERSON, C. C. Native copper, silver, and gold accessible to early metallurgists. *American Antiquity*. v. 36, n. 3, p. 286-321. 1971.

PÉREZ CAMPOS, X.; KIM, Y.; HUSKER, A.; DAVIS, P. M.; CLAYTON, R. W.; IGLESIAS, A.; GURNIS, M. Horizontal subduction and truncation of the Cocos Plate beneath central Mexico. *Geophysical Research Letters*, v. 35, n. 18, p. 1-6, 2008.

REVIE, R. W. *Corrosion and corrosion control: an introduction to corrosion science and engineering*. Hoboken: John Wiley & Sons, 2008.

ROBERTS, B. W.; THORNTON, C.P. (eds.). *Archaeometallurgy in global perspective: methods and syntheses*. Luxembourg: Springer Science & Business Media, 2014.

SEMO, E. *Historia del capitalismo en México, 1521-1763*. Mexico City: Editorial ERA, 1973.

STANSBURY, E. E.; BUCHANAN, R. A. *Fundamentals of electrochemical corrosion*. ASM International, 2000.

SUÁREZ, G.; ALBINI, P. Evidence for great tsunamigenic earthquakes (M 8.6) along the Mexican subduction zone. *Bulletin of the Seismological Society of America*, v. 99, n. 2A, p. 892-896, 2009.

VERMA, S.P. Absence of Cocos plate subduction-related basic volcanism in southern Mexico: A unique case on Earth?. *Geology*, v. 30, n. 12, p. 1095-1098, 2002.

WORLD TOURISM ORGANIZATION. *UNWTO Tourism Highlights 2017 Edition*. Madrid: World Tourism Organization, 2018.

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DOI: 10.36403/espacoaberto.2019.28384 ISSN 2237-3071