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Escuela de Ciencias de la Tierra, Energía y Ambiente

IS THE DETERIORATION OF CIVIL CONSTRUCTIONS RELATED TO USING NOT ADEQUATE VOLCANIC MATERIALS? CASE STUDY: IBARRA CITY

Trabajo de integración curricular presentado como requisito para la obtención del título de Geólogo.

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RESUMEN

El deterioro progresivo de las construcciones en la ciudad de Ibarra, Ecuador es evidente. Frecuentemente se ha asociado a este con el uso de materiales de origen volcánico como el basalto, la andesita, riolita, ceniza volcánica, o toba; principalmente en construcciones de uso residencial, comercial y estatal. Este deterioro se extiende incluso a construcciones importantes en el centro histórico de la ciudad. Esto ha desatado una gran ola de preocupación en la población en cuanto al tema de riesgos y gastos en remediación. El principal caso de deterioro que se puede observar es el deterioro por pérdida de material. Además, un 83% de la población ha afirmado presentar casos de deterioro por crecimiento de sales en sus hogares (eflorescencia). Este último, relacionado con la calidad de los materiales de construcción empleados, los cuales cuentan con grandes cantidades de material piroclástico fino y de sales primarias. Varios autores han catalogado el deterioro por sales como uno de los principales mecanismos en el desgaste de ladrillos y concreto. Sin embargos, las fracturas, la separación de materiales y el crecimiento de material orgánico son también de los principales tipos de deterioro encontrados. En el presente estudio, se han recolectado datos de deterioro en el centro histórico de Ibarra. Se ha podido demostrar que el deterioro por pérdida de material es el más común en construcciones antiguas, mientras que, en construcciones modernas se pueden observar mayormente casos de fracturas y eflorescencia. Donde fue posible, se tomaron muestras de sales secundarias y a partir de esto, se realizó el análisis de sales que permitió caracterizar los tipos de minerales presentes en las muestras, el origen de estos, y su posible efecto en las construcciones. Para la caracterización el método utilizado fue el análisis de fases minerales con ayuda del difractómetro de Rayos X de Polvo (DRX-P). Como resultado, se obtuvieron grupos de Sulfatos, Carbonatos, Nitratos, Silicatos y Boratos provenientes de componentes volcánicos utilizados en cementos. El mineral más común en estas muestras resultó ser la thenardita (Na_2SO_4), perteneciente al grupo de los sulfatos, presentes en el 79% de las muestras.

Palabras clave: deterioro, eflorescencia, crecimiento de sales, construcciones, cristalización, Ibarra.

ABSTRACT

Walking down the city streets of Ibarra you would be amiss to notice the tell-tale signs of deterioration. This deterioration is often associated with using volcanic materials such as basalt, andesite, rhyolite, volcanic ash, or tuff, primarily in residential, commercial, and government buildings. It is common to observe deterioration even in important constructions in the city's historic center. As a result, a wave of concern has arisen among the population regarding risks and remediation expenses. The main observed case of deterioration is material loss. Additionally, 83% of the population has reported cases of deterioration due to salt growth in their homes (efflorescence). The latter is related to the low quality of construction materials used, which contain significant amounts of fine pyroclastic material and primary salts. Several authors have identified salt deterioration as one of the main mechanisms in the wear of bricks and concrete. However, fractures, material separation, and the growth of organic matter are also among the main types of deterioration found. In this study, data on deterioration in the historic center of Ibarra was collected. It has been demonstrated that material loss is the most common form of deterioration in old constructions, while fractures and efflorescence are mostly observed in modern constructions. Where possible, samples of secondary salts were collected, and the salt analysis was conducted to characterize the types of minerals present in the samples, their origin, and their potential effect on constructions. The mineralogical characterization was carried out using X-ray Diffraction Powder Analysis (DRX-P). As a result, groups of sulfates, carbonates, nitrates, silicates, and borates originating from volcanic components used in cement were identified. The most common mineral in these samples was found to be thenardite (Na_2SO_4), belonging to the sulfate group, present in 79% of the samples.

Keywords: weathering, efflorescence, salts' growth, buildings, crystallization, Ibarra.

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1. INTRODUCTION

The weathering and deterioration of buildings occur naturally due to different agents and forces that are, in most cases, related to those that shape the geomorphological profiles in nature (Siegesmund & Snethlage, 2014). To have a deeper understanding of the deterioration processes affecting buildings, it is important to consider the quality and composition of the construction materials as they can strongly influence the decay rate of these. We know, for example, that strongly cemented sandstone layers are more resistant than porous, fractured weak cemented sandstone strata (Turkington & Paradise, 2005). On top of that, other aspects like moisture, heat, geodynamics, and exposure to an aggressive environment can strongly affect the conditions in which these buildings are preserved (Agyekum & Salgin, 2017; Wedekind et al., 2013).

The deterioration in civil structures is a global phenomenon in both rural and urban environments (Siegesmund & Snethlage, 2014), where it is the main cause of immeasurable economic losses in the remediation, reconstruction and preservation of houses, monuments, and buildings. In general, this deterioration is due to the natural aging process of the structures and other general parameters such as the quality of construction and materials used. As reported by (Balaras et al., 2005), in Europe, half of the budget used in the construction sector is spent on repairs, maintenance, and remediation. Moreover, this sector uses about one-third of all the raw materials and energy produced in Europe and over half of the electricity.

In Latin America, there is an enormous controversy surrounding the deterioration of civil structures since millions of dollars have been invested in the restoration and preservation of historical centers and monuments considered up to date as human heritage (Rojas, 2002; Oliveira et al., 2021). Construction materials in Latin America vary depending on costs, local availability, and specific building needs. Nevertheless, the most used building components in this region include concrete, brick, adobe, steel, glass, stone, wood, and ceramic tiles (Griffin & Ford, 2013). Additionally, all the previously mentioned materials can present different levels of deterioration in all types of constructions, which is particularly concerning for historical constructions as they were built in a previous epoch and under less rigorous parameters. At times, this problem has been attributed to the lack of interest of municipal governments in taking care of historical centers in the region (Hardoy & Gutman, 1991).

Ecuador is not the exception; the deterioration of civil structures is evident in every region throughout the country. Currently, we have only observed specific studies in the south of the country, that help us to give us an idea of the general damage that can be recognized on this area (Cardoso et al., 2018). However, these studies have been mainly focused on remediation instead of treating the fundamental issues that can provoke this type of phenomena.

Ibarra City, being part of the Ecuadorian highlands, exhibit a rich geological composition characterized by the interplay of volcanic and tectonic processes. Volcanic activity resulting from the subduction of the Nazca Plate beneath the South American Plate has given rise to the prevalence of andesite and basalt, which constitute prominent volcanic formations (Aspden & Litherland, 1992). These rocks, known for their robustness and aesthetic appeal, serve as viable options for construction materials. Furthermore, the highlands feature the occurrence of tuff, a lithological unit formed through the consolidation of volcanic ash. Tuff's lightweight nature and porous characteristics render it suitable for construction applications (Wedekind et al., 2013). The geological diversity of Ibarra City not only contributes to the region's geological allure but also offers prospects for utilizing these rocks in construction.

In Ibarra City, deterioration can be observed in constructions of all kinds and in any type of environment. The most used materials in Ibarra mainly originate from the nearby Imbabura volcano. Among these, we can observe andesite, basalt, volcanic ash and tuff, and rhyolite. High-degree deterioration can be found in constructions located along the main streets and avenues to the most hidden neighborhoods. This deterioration is reflected in the variation of color, texture, and other physical qualities of the façades. Most of this deterioration is caused by physical phenomena such as salt growth, fractures, deformations, alveolization, and aggressive chemical attacks and corrosion (Ellingwood, 2005). However, weather conditions play an important role in the conservation and deterioration of these.

Ecuador's climate is influenced by various factors, including its location near the equator, altitude, ocean currents, and prevailing winds. The country's proximity to the equator means that it experiences relatively stable temperatures throughout the year, with minimal seasonal variation (Morán-Tejeda et al., 2016). Likewise, altitude plays a significant role in determining the climate, with highland areas generally experiencing cooler temperatures than lowland regions. Climatological factors can not only affect the appearance of the building but also its structural stability due to the reactions produced by the interaction of outer conditions with the internal structure of constructions.

The most common minerals used in constructions include quartz and feldspars, used in glass and ceramics; limestones, which are used in the manufacture of cement and are composed of calcium carbonate; gypsum, which is used in the manufacture of plaster, drywall, and cement; and micas, used in insulation and as filler in plastic, paint, and asphalt (Horvath, 2004). However, these minerals can be accompanied by other secondary salts that may cause efflorescence and consequently the massive deterioration of these structures. Remediation is of crucial importance on this context since seismic activity on this area is very frequent and can aggravate the structural damages (Beauval et al., 2010). Currently, there are no deterioration studies held in Ibarra City that can help us to get an idea of the economic problem that this entails. Nonetheless, it is presumed that deterioration produces great economic losses both for the municipality and the population in general. These economic losses can go up to millions of dollars in assets if we compare it with case studies in similar cities in the Latin American region, as in the case of Pelourinho, the historic center of Salvador de Bahia in Brazil; Chorillos, an important urbanistic center in Lima, Peru; or Antigua, a historic city in Guatemala (Rojas, 2002).

Even though natural agents were pointed out as the main ones responsible for the deterioration of civil structures at first, it should be emphasized that an important part of this deterioration can be attributed to human-induced climate change in the last 50 years. According to (Huntley et al., 2021), the temperature increase due to human-induced climate change in recent years has influenced an increment in the evaporation rate in several regions around the world, generating a significant increase in the growth of salts on walls and rocks. This outcomes in a higher degree of deterioration of buildings, mainly in the middle and lower parts of concrete walls. It is presumed that this salt growth is due to various elements present in the construction materials used in civil works, such as evaporites and fine graine sands and cements. In Ecuador, mainly volcanic rocks are used in constructions of all kinds due to their abundance, determined by the geological environment (Campbell et al., 1974). According to the GAD Ibarra Land Management

Plan (GAD Ibarra, 2020), in Ibarra City we can find six quarries from which the stone material used for construction is exploited. It is hard to assess the type of material extracted from these quarries since private companies own these, but these materials can be associated with those found in Ibarra’s stratigraphy. The quarries that can be found surrounding Ibarra City are Terrazas del Rey, Alondra del Rey, Loma de Higos, Quebrada Blanca, Cantera Ramírez, and Terraza Quebrada Blanca. The location of these quarries is presumed to hold significant quantities of materials used in constructions such as basalt, andesite, tuff, and volcanic ash.

When studying the deterioration of constructions, it is necessary to consider some factors such as climate, general geology, and type of construction, since these can influence the level of deterioration and its characteristics. Various authors have classified deterioration into three types: physical, chemical, and biological (Viles, 2002). While other authors such as (Siegesmund & Snethlage, 2014));(Agyekum & Salgin, 2017))(Moreno et al., 2019) use more standardized systems to be able to explain different phenomena in a broader spectrum, such as the one proposed by the International Scientific Committee for Stone (ICOMOS-ISCS, 2008), which is going to be used for this work.

Studying deterioration forms in Ecuador is relevant due to the country's unique geological and environmental conditions. Ecuador is located in a seismically active region with diverse geological formations and climatic zones. Volcanic activity, high humidity levels, heavy rainfall, and coastal exposure pose challenges to infrastructure, buildings, and cultural heritage sites. Understanding the specific forms of deterioration, such as erosion, cracks, deformation, and biological colonization, allows for developing effective conservation and maintenance strategies. By comprehending the underlying causes and processes of deterioration, researchers, engineers, and conservationists can implement targeted measures to mitigate damage, preserve cultural heritage, ensure infrastructure safety, and foster sustainable development in Ecuador.

1.1 Problem statement

Weathering in Ibarra’s buildings has become more evident over the last decades. It is sufficient to walk through the historic center and around the most touristic places to detect the high degree of deterioration that is exposed in these areas. There are many reasons for this, including municipal authorities’ carelessness and the natural aging of these constructions. Regional civil weathering is considered a major issue on the preservation of historical centers and monuments (Siegesmund & Snethlage, 2014). As part of the Imbabura’s UNESCO geopark project, Ibarra is considered one of the main spots for geoturism in Ecuador. With this background, and considering the high deterioration rate observed, we can have an idea of the reasons why this city has the focus on this study.

Currently, no studies can provide us with a basic idea on the level of deterioration and the causes for this in houses and monuments of the city. Consequently, corrective measures have not been taken for this sort of issue other than repairing the structures superficially by homeowners and the municipality. Since those problems are not being solved from the foundations, they end up being regular, which causes high and regular maintenance expenses. The most common types of deterioration are cracks, loss of material, biological colonization and salt deterioration.

Although salt growths are more common in arid and semi-arid environments (Springer, 2008), Ibarra City, is also very prone to the growth of some highly soluble salts due to its geology and climatological situation. This is because the city's civil structures are built with materials from areas where soil salinization is very common, caused by various factors such as the high rate of evaporation and the high content of chlorides, nitrates, carbonates, and sulfates in natural environments. Therefore, Ibarra City is susceptible to deterioration caused by the growth of salts, and when these materials encounter the humidity of the environment, salts filter through the pores of the different construction materials, and then crystalize when they dry (Rodriguez-Navarro & Doehne, 1999).

1.2 Objectives

1.2.1 General Objective

Assessment of the impact of volcanic materials on urban deterioration in Ibarra City through GIS Mapping and X-ray Diffractometry (XRD).

1.2.2 Specific objectives

- Record types and deterioration status using GIS and analyze their distribution in the city's historical center.
- Obtain information about deterioration and localize the most deteriorated areas.
- Determine the most common minerals present in the primary salts analyzed and their estimated provenance.
- Estimate the relative damage of buildings due to deterioration.
- Correlate the main secondary groups of salts found in the study area with those that can be found in different urban environments.

2. GEOGRAPHICAL AND GEOLOGICAL SETTINGS

Ecuador is located on the west coast of South America and is home to diverse geological features, including active volcanoes, mountain ranges, and vast rainforests. This country is situated on the boundary between the Nazca and South American tectonic plates, whose collision formed its most dominant geological feature, the Andes Mountain Range (Mégard, 1987). The Ecuadorian Andes are part of the more extensive mountain range that stretches over 7,000 km along the western coast of South America and are characterized by steep slopes, high peaks, and deep valleys (Bigazzi et al., 1992). A variety of sedimentary, volcanic and metamorphic rocks depict this mountain range. These rocks were formed from sediment deposits in the area when a shallow sea covered it during the Cretaceous Period (145 to 66 million years ago) (Litherland et al., 1994). Over time, these sediments were compressed and transformed into metamorphic rocks due to the high temperatures and pressures present in the Earth's crust (Litherland et al., 1994). Finally, the region’s youngest and most abundant lithological units comprise a wide variety of volcanic rocks that reflect the area’s ongoing tectonic and volcanic activity.

The Andes of Ecuador are divided into three main ranges: the Western Cordillera, the Interandean valley, and the Eastern Cordillera or Cordillera Real. The Western Cordillera is the highest and most volcanic range, with peaks over 5,000 meters above sea level. Deep canyons and narrow valleys characterize the Interandean Valley, while the Cordillera Real is lower and more gently sloping, with peaks averaging around 2,500 meters above sea level (Campbell et al., 1974).

Imbabura province is located in the northern part of Ecuador (Fig. 1a), between the western foothills of the Cordillera Real and the Western Cordillera, in the Interandean valley. It is named after the Imbabura Volcano, the area’s most prominent geological feature. Linear belts of metamorphic rocks dominate the Cordillera Real to the east (Ambuquí phyllites) (Litherland et al., 1994), intruded by early Mesozoic S-type and I-type granites (Pimampiro granite), and Cenozoic volcanic sediments cover these. Late Mesozoic eugeosynclinal sediments dominate the Western Cordillera to late Cretaceous syn-orogenic sediments, intruded by diorite and granodiorite intrusions (Campbell et al., 1974). According to (Jaillard et al., 2005), many petrographic and geochemical studies of the Western Cordillera show the accretion of oceanic plateaus of the Cretaceous age to the western margin of Ecuador.

Furthermore, the Interandean depression is an extensional structure bounded by faults and comprises recent volcanic sediments from the nearest volcanoes. It also includes epiclastic and distal volcanoclastic sediments, primary and reworked, of inferred Plio-Quaternary age and surface deposits (glaciers, lahars, terraces, lagoons, colluvial and alluvial deposits).

Geographically, Imbabura Province is bordered to the north by the province of Carchi, to the south by the province of Pichincha, to the east by the province of Sucumbíos, and to the west by the province of Esmeraldas. The capital of the province is Ibarra City, where there is an altitude variation between 2180 and 2360 meters above the sea level (Fig. 1b). This presents reliefs that range from semi-flat areas to areas with slopes of up to 70° (Pennec et al., 2011). Regionally, the area belongs to the Intra-Andean basin known as the "Hoya Del Chota", the same that extends longitudinally within the Interandean valley, forming a large trough, surrounded on its edges by the Western Cordillera and by the Cordillera Real de Los Andes, limited by the Nudos del Boliche and Mojanda-Cajas to the north and south respectively.

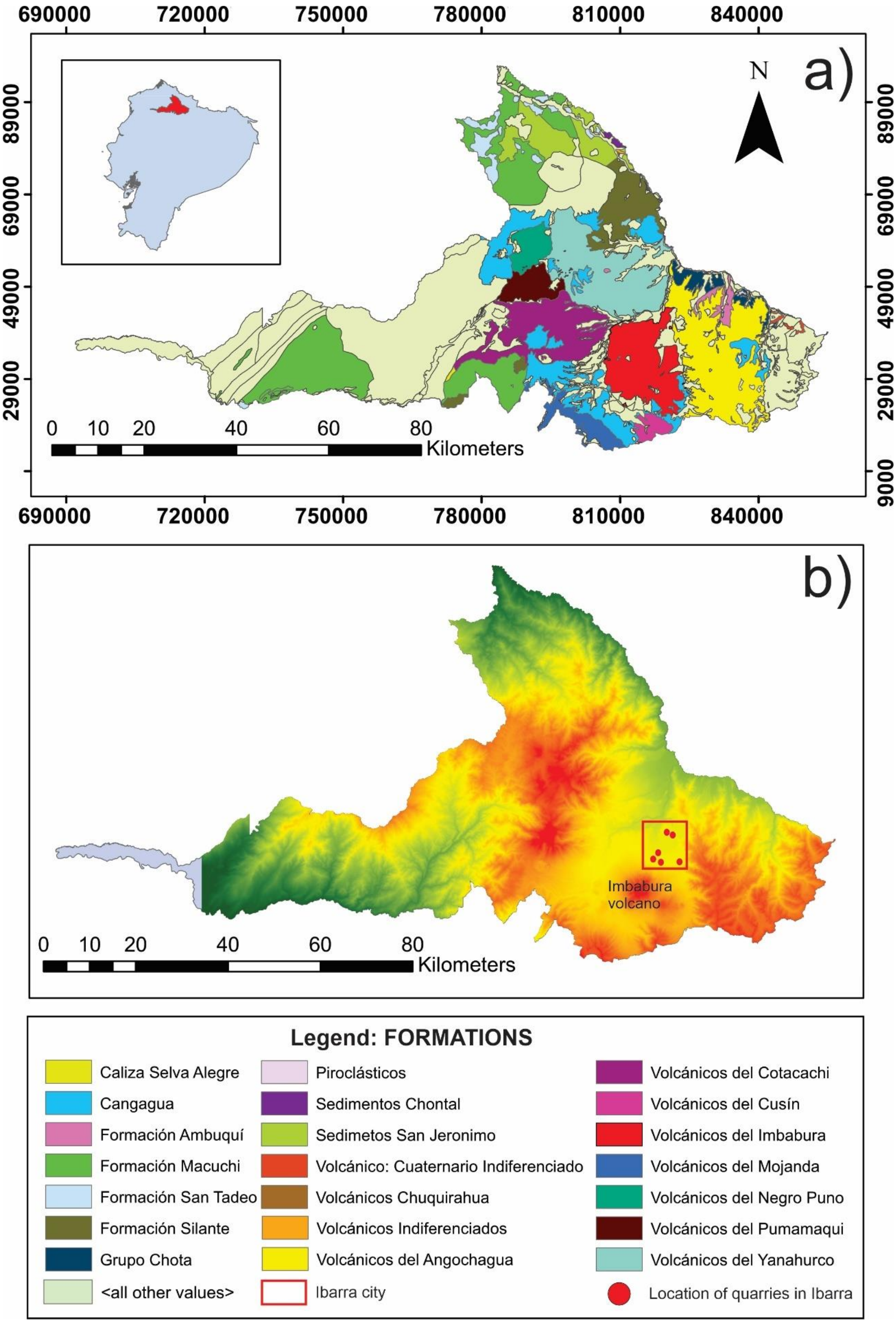


Figure 1. Map of the Imbabura province using a WGS84 Datum. a) Imbabura map of geological units b) Digital terrain model of the province of Imbabura (12m resolution) showing Ibarra City in a square at the north of the Imbabura volcano. Data was not available for the occidental part of the map.

Ibarra is located in the southeastern part of the Imbabura province, to the north of the Imbabura volcano, an area until now considered tectonically active. This area is surrounded by other volcanic complexes, Cubilche to the South-East, Cotacachi-Cuicocha to the West, and Mojanda and Cusin to the South. Among the geological sites of greatest interest in Ibarra City are the Yahuarcocha lake and the Imbabura volcano, which is part of the Andes volcanic chain.

The Imbabura volcano is located in the Western Andes (Campbell et al., 1974), a region characterized by Mesozoic and Cretaceous sediments with intrusions of diorite and granodiorite. Ibarra City is comprised mostly of volcanic materials from the Imbabura volcano, which erupted from the upper Pleistocene to the early Holocene (Andrade et al., 2018). Being 'Volcanicos del Imbabura' the predominant unit in the city. The Imbabura volcano deposits were formed by lava flows, pyroclastic flows, and debris avalanches, with two main volcanic edifices - Imbabura I and Imbabura II (Pennec et al., 2011).

Imbabura I is the oldest edifice, consisting of five units with massive andesitic affinity lava packages and dips ranging from <10° in the lower areas to 20°-30° in the upper areas. The Debris Avalanche is the largest unit of Imbabura I, with a minimum volume of 1.55 km3, covering an area of 155 km2, and extends from Ilumán to the northern zone of Ibarra. The Imbabura II comprises the upper cone of Taita Imbabura, pyroclastic deposits, and the Huarmi Imbabura volcano. A significant event of this unit is the "pyroclastic flow of the Tahuando River," consisting of pyroclastic flows and ash with an approximate thickness of 30 meters.

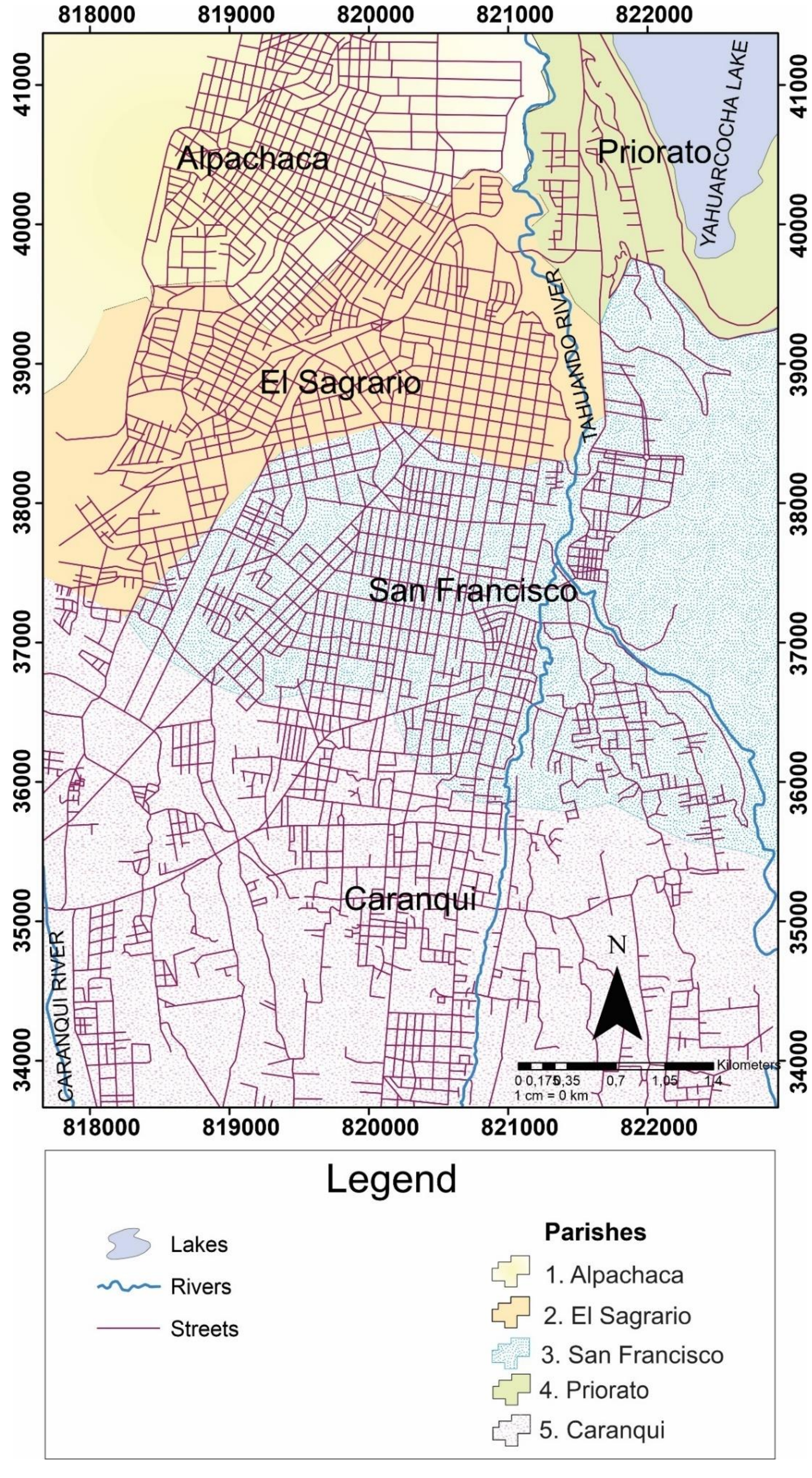


Figure 2. Map showing the street view of the Ibarra city and its five urban parishes. For this study, each parish is taken as a zone. Datum: WGS84

Ibarra City (Fig. 2) was founded in the year 1606 by Cristóbal de Troya (Coronado-Martín & Cala-Aiello, 2016), and from that date, there's records of the construction of Ibarra's cathedral, which was completed in the year 1650. Three years later, La Merced church was built, and after this, in 1672 the churches of San Agustín and Santo Domingo were constructed, forming the first parishes of the city. The materials used for the construction of these include carved volcanic and sedimentary rocks, basalt, andesite, rhyolite and limestone. Even though these were the most important landmarks at that time, the first settlements of the city were established years before its foundation, being the oldest church on which data is available is the Iglesia del Señor del Amor de Caranqui, built in 1604 using the same materials, two years before the foundation of Ibarra, although the current church was rebuilt in 1940 (Bedoya et al., 2018). After the earthquake of August 16, 1868, which had an estimated magnitude of 7.25 on the Richter scale (Beauval et al., 2010), the city underwent a series of reconstructions that focused on the main churches of the time, the Cathedral (1878) and the churches La Merced (1933), San Agustín (1935) and Santo Domingo (1923). There is no reliable information of the first houses that were rebuilt after the seismic event of 1868 at the moment, but it is presumed that they were located in the center of the city, near the churches of La Merced and the cathedral (Coronado-Martín & Cala-Aiello, 2016).

Currently, Ibarra City has experienced a significant growth in terms of infrastructure and population. According to the most recent census conducted in Ecuador in 2010 (INEC, 2010), the population of Ibarra was 181,175, residing in 36,976 private homes in the 5 urban parishes in the city, Alpachaca, El Sagrario, San Francisco, Priorato, and Caranqui. These parishes are characterized by higher population densities, infrastructure, and a more developed environment. With this, we can gain a comprehensive understanding of the importance of this study and obtain an overview of the historical buildings' ages in Ibarra dating back 154 years and further. Despite the aforementioned, it is important to underscore that the degree of degradation observed in these churches and historical constructions is moderate when juxtaposed with modern constructions. This may be attributable to the fact that the construction materials employed in these edifices differ substantially from those commonly utilized in contemporary building practices.

2.1 Environmental Conditions

According to the Köppen-Geiger's classification scheme (Kottek et al., 2006), the central part of the Imbabura province, in view of its location and geological features, falls in the type C type of climate (Fig. 3), which is given to temperate Mediterranean climates. However, Ibarra City has a great variety of microclimates, defined by the existing orographic conditions (relief, altitude, etc.), the oceanic air masses, and air masses or trade winds of the Amazon basin, ranging from warm humid to warm dry. Ibarra is located in a temperate climate zone due to its altimetric position: 2,418 meters above sea level on average (Fig. 1b) (Donoso-Vallejo, 2012). The average winds in Ibarra City are of the order of 7m/s as a maximum and 3.5 m/s as a minimum.

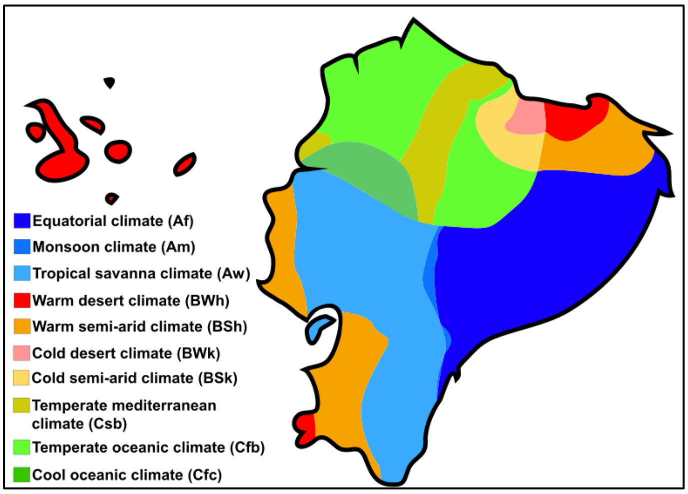


Figure 3. Ecuador map of Köppen climate classification. (Zifan, A., 2016)

Currently, there are temperature and precipitation data taken by the Meteorology and Hydrology National Institute (INAMHI) at Ibarra-INHAMI station (M1240), which is located in the Caranqui parish, 200 meters from the old Ibarra-Airport weather station (M053). From the data published in the Meteorological Yearbook of INAMHI (2021), we can conclude that the climate of Ibarra varies from rainy subtropical to dry subtropical, with a temperature range averaging 11.2 – 23.5 °C throughout the year. According to (Pourrut, 1983), the climate in Ibarra City is classified in:

- Semi-humid to humid mesothermal equatorial, for heights between 1500 meters above the sea level (m.a.s.l), and 3000 m.a.s.l.
- Very humid cold equatorial-high mountain, above 3000 m.a.s.l.

3. FORMS OF DETERIORATION

There are several forms of weathering that result from the interaction between stone structures and the environment. These can be divided according to the agent that produces them in chemical, physical and biological. However, to simplify the understanding, we are going to employ a more standardized system, which was the one proposed by the International Scientific Committee for Stone (ISCS). This classification divides the types of weathering in five categories according with the physical attribute they show on their façades, as seen in *Table 1*.

Table 1. Terms used for the characterization of stone deterioration (ICOMOS-ISCS, 2008).

Crack and deformation	**Detachment**	**Features induced by material loss**	**Discoloration and deposit**	**Biological colonization**
Crack (Fracture; star crack; hair crack; craquelé; splitting) Deformation	Blistering Bursting Delamination Desintegration (Crumbling; granular desintegration like powdering, chalking, sanding, sugaring) Fragmentation (Splintering; chipping) Peeling Scaling (Flanking; contour scaling)	Alveolization (Coving) Erosion (Differential erosion; loss of components or of matrix; rounding; roughening) Mechanical damage (Impact damage; cut; scratch; abrasion; keying) Microkarst Missing Part (Gap) Perforation pitting	Crust (Black crust; salt crust) Deposit Discoloration (Coloration, bleaching, moist area; staining) Efflorescence Encrustation film Glossy aspect Graffiti Patina Soiling Subflorescence	Lichen Moss Mold Plants

Table 1 shows the standard international classification for deterioration proposed by the ISCS in 2008, which will be adopted in this study, for civil structures in Ibarra City. It should be noted that these types of deterioration in many cases can coexist in heterogeneous construction types. Similarly, there are cases where a type of material can be observed in several structures, but with a different degree of deterioration. On that case, it usually depends on the level of exposure to external agents or the age of the construction. Another frequently encountered scenario in civil structures involves the localized deterioration of specific sections, while other areas remain unaffected. In Ibarra City, a noticeable deterioration can be noted in certain areas, these being of different types

and, most of them, due to physical factors. Understanding these deterioration patterns may give us an idea about the importance of mapping the distribution and frequency of all different forms of deterioration.

3.1 Crack and deformation

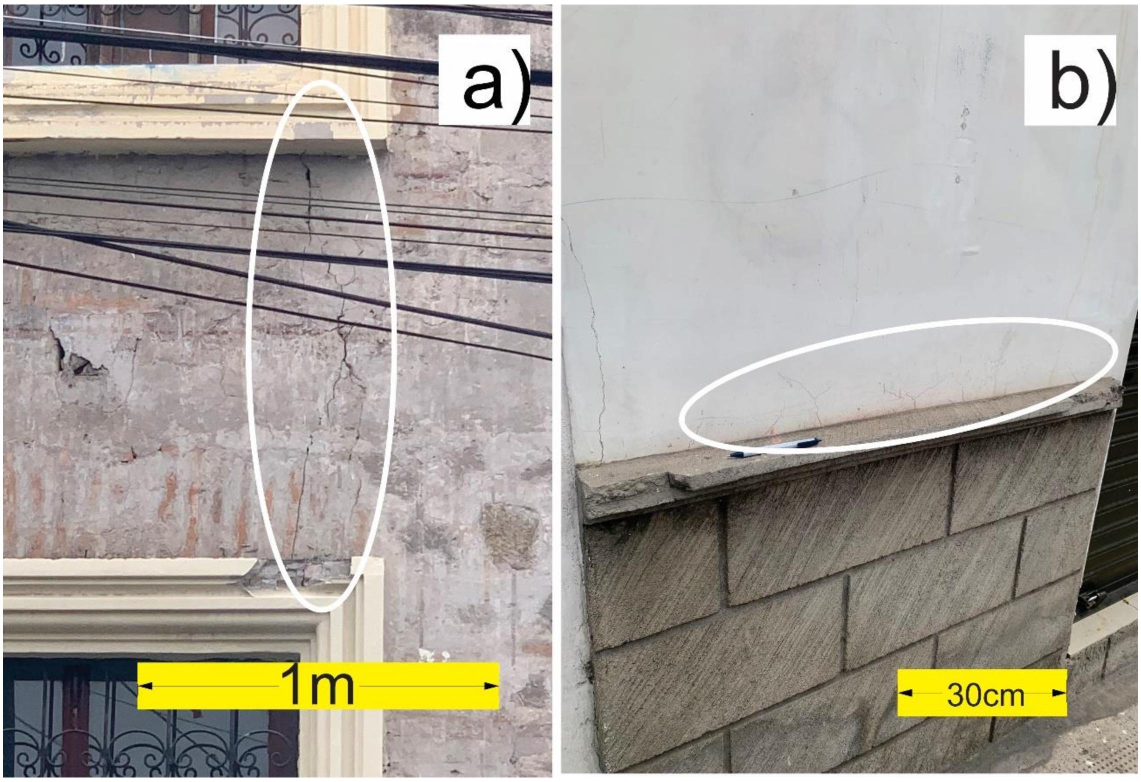


Figure 4. Deterioration by cracks, a) Upper part of a three-floor construction with >1m cracks. Juan Jose Flores street & Vicente Rocafuerte b) Middle part of a concrete wall with microcracks of <1mm. Rafael Troya street & Antonio José de Sucre.

Cracks are defined as a structural discontinuity shown as an opening displacement between opposite walls due to a stress component exceeding its strength component due to, in most cases, externally applied loads (Chitte & Sonawane, 2018). These are generally preceded by a deformation originated by an external factor. This type of deterioration falls into the category of physical deterioration and is highly dependent on the hydraulic capabilities of the building materials. Cracks (Fig. 4a), usually start with minor imperfections, also known as fissures, that are exposed mainly on the material’s surface. Cracks can be caused by various phenomena such as freeze-thaw cycles, alkali-aggregate expansion and the desiccation shrinkage of concrete (Terada & Kurumatani, 2010).

Concrete cracking is typical and easily repairable as long as there is no major underlying problem. However, when these occur over and over, it is necessary to conduct and in-depth study of the material's resistance and the stress to which the structure is subjected (Lundin et al., 1996). They can appear in different shapes and sizes, the largest being those that have been subjected to a greater stress, however, it should be considered that those of smaller size, micro-cracks (Fig. 4b), are produced by the same stresses and are naturally followed by a fracture.

3.2 Detachment

Figure 5. Detachment cause by blistering, a) Concrete detachment in a wall of a local shopping building in the historical center of the Ibarra city, Simon Bolivar avenue & Jose Mejia Lequerica, b) Detachment in paint coat in the lower middle part of a house in the historical center of the city, Antonio José de Sucre avenue & Jose Mejia Lequerica.

One of the most common forms of deterioration in the external layer of the walls is detachment; this often affects the paint coating of the houses and the concrete surfaces producing peeling or blistering. Blisters originate from fluid pressures underneath the coating, which pulls it away from the surface; this is always preceded by peeling. Blisters can also be the leading cause of bursting, delamination and scaling. Following Agyekum & Salgin (2017), blisters are correlated with dampness increase in buildings, and they usually depend very little on the quality of the materials used. These are generally found to be hollow, but can also be found filled with water as soon as the blistering conditions are maintained. On painting coats (Fig. 5b), this failure is caused by abnormal conditions in which the affected constructions are built. These can be rainwater leaking through cracks or moisture originating within the buildings (Browne, 1953). Meanwhile, this phenomenon can also bedeveloped in concrete structures with drastic changes in the daily temperature (Hailesilassie & Partl, 2012). However, other factors as the fluctuation of the pressure inside blisters can also influence (to a lower degree) the blisters' growth in concrete (Fig. 5a).

3.3 Features Induced by Material Loss

This type of deterioration is characterized by the loss of material influenced by diverse agents of physical origin, including erosion and alveolization. In many cases, this can also be a consequence of cracking or detachment, making this type of deterioration one of the most common and observable in the environment. Alveolization, also known as honeycomb weathering (Fig. 6c), is a form of degradation characterized by the mechanical intervention of water and wind to shape deeply eroded cavities on rocks. As Moreno et al. (2019) reported, alveolization and high alveolization primarily affect stone reinforcements on the base of the walls. On the other hand, erosion can be described as the process that produces materials to wear out due to natural agents like water or wind. The difference between this and alveolization is that erosion does not create a specific pattern on rocks. It only removes soil, rock or any dissolved material and relocates these so they can be redeposited (Fig. 6b).

Figure 6. Features induced by material loss in the historical center of Ibarra, a) Mechanical damage, Simon Bolivar & Miguel Oviedo str., b) Erosion, Vicente Rocafuerte & Miguel de Oviedo str., c) Alveolization, Episcopal Chapel, Pedro Moncayo str., d) Missing part, Simon Bolivar & Eusebio Borrero str.

Mechanical damage is also considered in this section (Fig. 6a). Even though there is a limited understanding of the main drivers, it can be purported to be segments of rock that have gone through a strong level of abrasion or impact damage. They can be human induced in many cases, but the quality of materials and environmental factors also impact these. Generally, moisture has been widely suggested as one of the main precursors to rock breakdown, associated with weathering, regolith production and/or erosion (Eppes & Keanini, 2017). The types of deterioration previously mentioned can lead to gaps (or missing parts) in civil structures (Fig. 6d). Gaps usually take more time to happen but are strongly dependent on the level of abrasion the structure has been subjected to.

3.4 Discoloration and Deposits

This type of deterioration includes the appearance of crusts, deposition of materials, discoloration of structures, and efflorescence (ICOMOS-ISCS, 2008). These are produced by both physical and chemical factors and in the long run, they entail higher economic losses than the other types. Naturally, different types of alterations could be added to this section, such as those caused by graffiti, soiling and glossy appearance, but considering that these types of deterioration do not entail a high level of degradation, they will not be considered for this study. Hence, the damage that causes the most concern in the general population is the one produced by efflorescence (Fig 7). That is why the focus of this section will be efflorescence its deterioration.

3.4.1 Efflorescence (Salt Weathering)

This is one of the most observed types of deterioration in homes in Ibarra City, both outside and inside. Efflorescence is a surface deposit of salts that usually affect constructions or historical monuments. This growth can occur in different types of materials (brick, concrete, paint, etc.; Fig. 7), and is produced when a wall, enriched to some primary salt, is subjected to humidity from the environment, which moves through the substrate dissolving these mineral salts and forming crystals when they dry (Zehnder & Arnold, 1989). Alternatively, when this salt growth occurs deep within the pores of a solid matrix, it is known as subflorescence. This latter can be, at times, very destructive since it can produce a physical disruption in the physical coherence of the matrix, causing its rupture (Dow & Glasser, 2003). Despite this, efflorescence on buildings is mainly analyzed because the sampling process has been non-intrusive and only superficial samples have been considered.

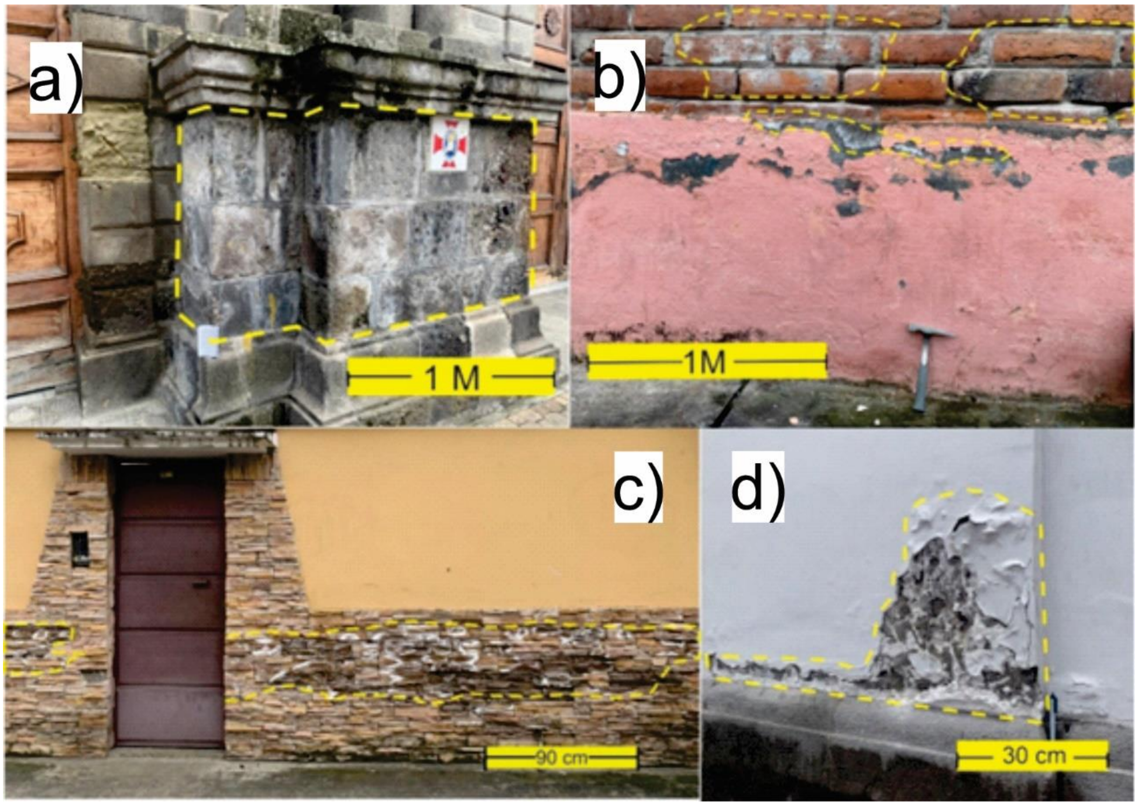


Figure 7. Efflorescence in different materials in Ibarra City, a) Carved igneous rocks, Catholic Cathedral of Ibarra, b) Bricks, Atahualpa ave. & Tobías Mena, c) Sedimentary carved rocks, Jacinto Egas ave. & Tobías Mena d) Concrete,Pedro Vicente Maldonado ave. & Juan Jose Flores.

Some sites considered until now as World Heritage Sites by UNESCO are afflicted by salt crystallization and weathering. Among them we can find El-Merdani Mosque in Cairo, Egypt (Fitzner & Heinrichs, 2001), the ancient city of Petra in Jordan (Wedekind & Ruedrich, 2006), and the Muñoz Chapel of the cathedral of Santa María in Cuenca, Spain (Martínez-Martínez et al., 2021). Given these scenarios, it is natural to assume that this phenomenon will likely occur at essential sites in our locality. Considering that Ibarra City is part of the UNESCO World Geopark, the losses could be economical and go further, putting a World Heritage Site at risk.

Weathering due to salt growth is a problem as long as there is an abundant supply of salts (supersaturation), adequate environmental conditions (high evaporation rates) and materials that are vulnerable to this type of deterioration. (Rodriguez-Navarro & Doehne, 1999). Naturally, arid environments are the most prone to salt deterioration due to higher evaporation rates (Springer, 2008). However, the salinization of soils can also be derived from air pollutants, coastal salt spray, deicing salts and the local geology. Thus, salt weathering can potentially affect an extensive range of environments. In the specific case of the Imbabura province, it can be inferred that one of the most significant factors for the salinization of soils can be related to the accretion of oceanic terrains on the western cordillera. However, salts can also occur as veins in volcanic rocks (Holtkamp & Heijnen, 1991).

Several authors have addressed salt growth as a common problem in construction materials with high porosity. (Brocken & Nijland, 2004)(Pel et al., 2004). Efflorescence is also known to increase depending on climatic conditions, human interference, type of materials, etc. Nevertheless, it is important to understand how salt growth can affect different structures and why it is considered one of the most aggressive forms of deterioration nowadays (Neville, 2004). Currently, there are ways to fight against the effects produced by salt weathering, but these entail moderately high efforts and costs.

The crystallization of salts is one of the most common causes of significant deterioration in monuments and buildings (Charola et al., 2007). The development of salt crystals causes an increase in the volume of these mineral phases, which causes tensions in the pores and fissures of the rocks (Choo & Sun, 2018). If liquids allow salt transport, evaporation, which can occur both on the surface (efflorescence) and inside a material (subflorescence), regulates its crystallization. Furthermore, the longer a saline solution remains in the pores, the greater the damage it can sustain to building materials (Ruiz-Agudo et al., 2006).

3.4.2 Problems faced in the study of salt weathering.

One of the main problems in the study of deterioration by salts is the variables that are not considered at the nanometric scale when making in-situ analyses (Doehne, 2002). A great variety of chemical processes occur in porous rocks that contain salt growths (subflorescence), and we cannot take them into account due to the non-invasive techniques used. In addition to this, it should be emphasized that not all salts act in the same way, so the properties of both the solution, the substrate, the salts and the environment must be considered when studying salts too.

The short understanding of the kinetics of the pore solution zone in the materials can also affect the way we see the topic of salt weathering. A pore solution zone is place generated in the porous part of the material that is in contact with air due to wick action influenced by the exposure conditions (temperature and humidity); (Liu et al., 2014). The small number of studies that have been carried out in this area leaves us with a large gap regarding the general behavior of salts, the formation of deterioration and the processes in chemical reactions. Then as well, this could give us an idea of how to prevent salt deterioration.

3.4.3 Common salts in the environment

Haynes & Bassuoni (2011) stated that salts that produce weathering in concrete in order of aggressiveness include sodium sulfate, calcium carbonate and sodium chloride. However, other salts like calcium sulfate, sodium nitrate and calcium borate are also known to produce weathering on different materials. The most common types of salts in concrete are sulfates (Nord, 1992) The most common types of salts in concrete are sulfates (Kumar & Kameswara Rao, 1994; Zapata, 2022).

Dana classification has been used to define and classify the salts found in efflorescence samples. Through this, we can better categorize the minerals encountered and their contribution to the deterioration of constructions based on their crystal structure. Studying the crystallography of minerals is believed to be important in investigating deterioration caused by salt growth, as it provides insights into the size, shape, and arrangement of salts during efflorescence (Ferraiolo, 1982). The geometric arrangement of salt crystals also aids in understanding their solubility and estimating structural damage (Zehnder & Arnold, 1989). Crystal systems often associated with minerals exhibiting higher solubility include orthorhombic, and monoclinic systems (Zapata, 2022). Based on the most common compounds found in efflorescence samples in urban environments, a brief overview of their salts will be presented to understand their general behavior.

3.4.3.1 Sulfates

Sulfates encompass a category of minerals and chemical compounds characterized by the presence of the sulfate ion (SO_4^{2-}), composed of one sulfur atom bonded to four oxygen atoms (White, 2018). They are frequently encountered in nature as independent minerals and integral components of mineral formations.

Sulfate-rich salts may appear in the environment as result of the oxidation of sulfides. Sulfate salt weathering is often responsible for concrete deterioration in evaporation zones (Liu et al., 2014). One of the main problems related to soil sulfidation is sulfate-induced heaves (Kota et al., 1996). These are upward movements of the surface that respond to triggering variables like moisture or changes in temperature. However, the cations associated with these sulfates can strongly influence the decay of the construction materials. As Kumar & Kameswara Rao (1994) stated, sodium sulfate affected the degree of deterioration in types of cement compared to other sulfate solution cations.

3.4.3.2 Carbonates

Carbonates are chemical compounds that contain the carbonate ion (CO_3^{2-}). They are formed when a metal or positive ion combines with the carbonate ion (White, 2018). Carbonates are abundant in nature and play important roles in various geological processes. In efflorescence, carbonates typically come from sources such as cement, mortar, or the surrounding environment (Martínez-Martínez et al., 2021). When water infiltrates into porous building materials, it dissolves soluble salts present within them. Carbonate salts, such as calcium carbonate ($CaCO_3$) or sodium carbonate (Na_2CO_3), can be among these dissolved salts.

The action of water drives carbonation in concrete. Carbonation is increased by the presence of alkali, sodium, and potassium (Kobayashi & Uno, 1990). Carbonates may develop according to the following reaction:

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$$

This equation proposes the relation of the carbonation with the composition of the pore solution in concrete. Like sulfate salts, carbonates can undergo under several expansive changes when exposed to temperature and humidity changes. Although, under the same conditions, carbonates can be less destructive than sulfates (Haynes & Bassuoni, 2011).

3.4.3.3 Nitrates

Nitrates are chemical compounds that contain the nitrate ion (NO^{3-}) (White, 2018). They are formed when nitrogen compounds, such as ammonia (NH_3) or nitrogen dioxide (NO_2), react with oxygen (O^2) in the presence of other elements (Donoso-Vallejo, 2012). Nitrates are commonly encountered in various forms, including solid salts, liquid solutions, or gases.

The case of nitrates is more complex than the previous ones. Although it is also found in concrete walls, it is much more common indoors than outdoors. Also, they don’t normally show effloresce since these come from the action of nitrifying bacteria, organic matter or human activity (paint, spackling paste, etc.) (Fernández Ibáñez, 2003; Laue et al., 1914). Since nitrates are very hygroscopic (Laue et al., 1914), they tend to disappear in environments that are highly exposed to rain and wind. As for the mitigation of these, it does not entail a significant problem due to the aforementioned. According to Doehne (2002), when trying to mitigate salt growth using highly absorbent materials, nitrates and chlorides are the easiest to remove. On the other hand, sulfates and carbonates represent the most prominent threats when using salt poulticing techniques.

3.5 Biological Colonization

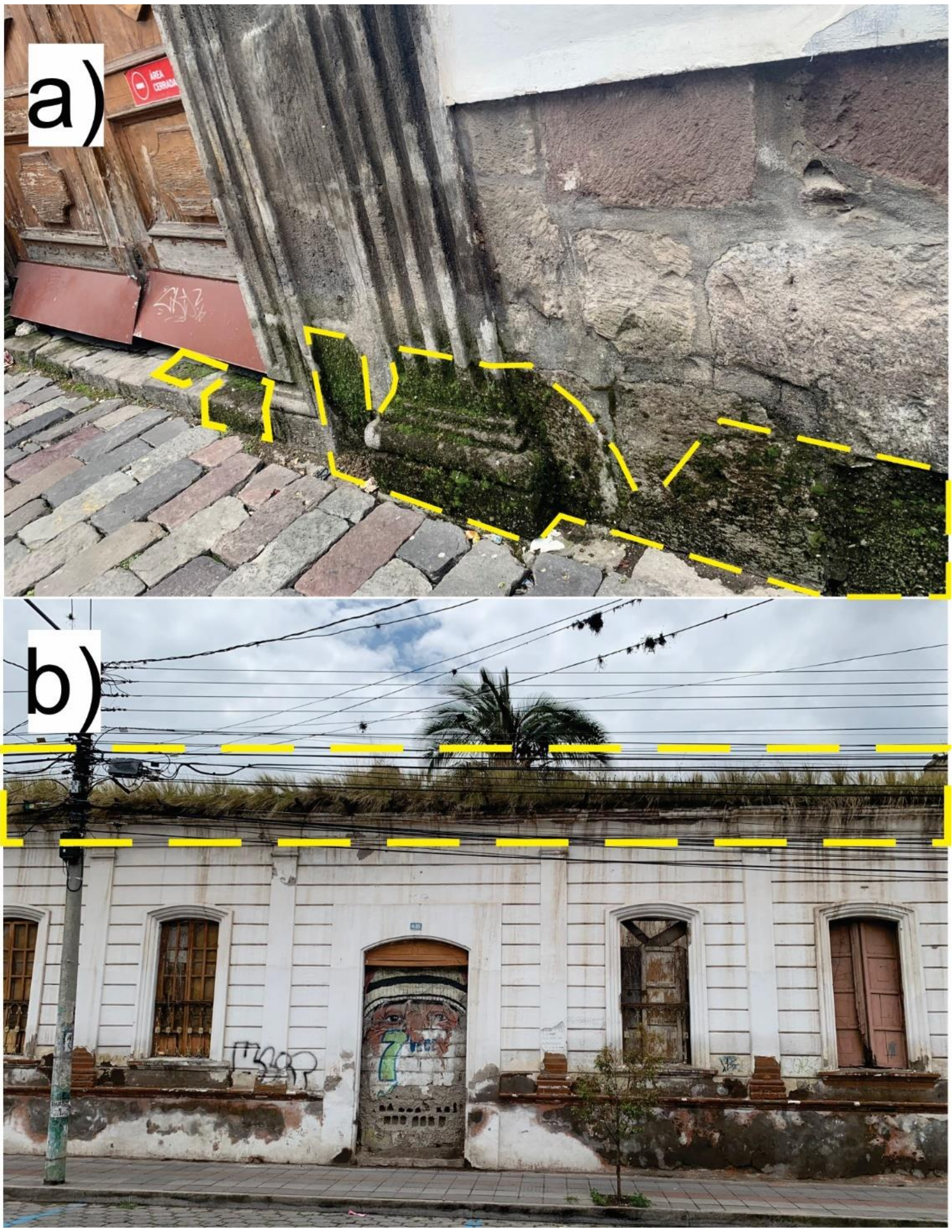


Figure 8. Deterioration by biological colonization in the historical center of Ibarra, a) plant growth in the bottom part of a concrete structure, Catholic Cathedral of Ibarra b) severe deterioration on a house ceiling due to root growth, Pedro Vicente Maldonado & Miguel Oviedo.

The biological colonization is one of the most curious cases on which weathering can show up in the environment. Although the previous weathering types are very important factors in the deterioration of concrete, biological activity also plays a predominant role due to its interactions with the materials (Fig. 8). The presence of macro and microorganisms of plant, animal or fungal origin on concrete structures can not only affect the environmental comfort and aesthetics of buildings, but can also cause a wide variety of physical, mechanical, chemical or biological damage and defects (Nowicka-Krawczyk et al., 2022). In the case of microorganisms (Fig. 8a), bacteria (including actinomycetes and cyanobacteria), fungi, algae, protozoa, and other small animals, have been found to form biofilms on the surface of stone and painted buildings (Gaylarde P. & Gaylarde C., 2002). Moreover, vegetation on top of a structure can retain water on the concrete surface (Fig. 8b), leading to saturation of the material and thus causing physical damage through wetting-drying cycles (also known as freeze-thaw damage), especially in tropical climates (Zhang et al., 2020). This same vegetation can also cause mechanical damage due to the penetration of the roots of plants, bushes and trees, through joints, fissures and weak points, which, as they grow, generate expansion forces that increase deformation and deterioration. In the case of Ibarra City, this type of deterioration is less common than the rest due to Ibarra’s mostly dry type of weather.

4. METHODOLOGY

To meet the objectives of this work, a bibliographic compilation has been carried out, which has been divided into three parts. In the first part of this literature review, information about types of weathering in different environments and with varying types of exposures was collected. In order to determine what types of deterioration were the most common in Ibarra City, a broad bibliography about the history of the city's main churches, which were rebuilt after the seismic event of 1868 was obtained. With this, we can better understand the ages of the older constructions in the city to estimate their conditions. In addition, it was observed the type of modern constructions that we can find around the city. The third and final stage of bibliographic collection focused on finding the most common types of deterioration in urban environments and prevention and remediation methods.

For the practical part, a deterioration description and analysis on the external structures of buildings in Ibarra City was carried out to twenty-six blocks along the historical center of the city (Annex 1). This area was considered since apart from being one of the most touristic areas of Ibarra, we can also find constructions of a wide range of ages and very varied types of materials. In this case, recent constructions (less than 2 years old) and older constructions (more than 150 years) were analyzed. Different materials have been used in these constructions, many of them of igneous origin. In order to have a better visualization of the survey carried out in each of the 41 points in the historic center, a map has been made using the ArcMap software (see Fig. 9). All the maps presented in this work were constructed using the UTM (Universal Transverse Mercator) coordinate system, WGS84, 17N.

The technique used to classify the type of weathering in the study area was comparing the observation of the deterioration patterns found with those described in the bibliography. On the other hand, a chemical analysis of salts using the X-Ray Diffractometer (XRD) was carried out to unveil the most common minerals found in salt growths. For this efflorescence study, five urban parishes of the Ibarra canton have been analyzed, among which we find: Alpachaca (Zone 1), El Sagrario (Zone 2), San Francisco (Zone 3), Priorato (Zone 4), and Caranqui (Zone 5).

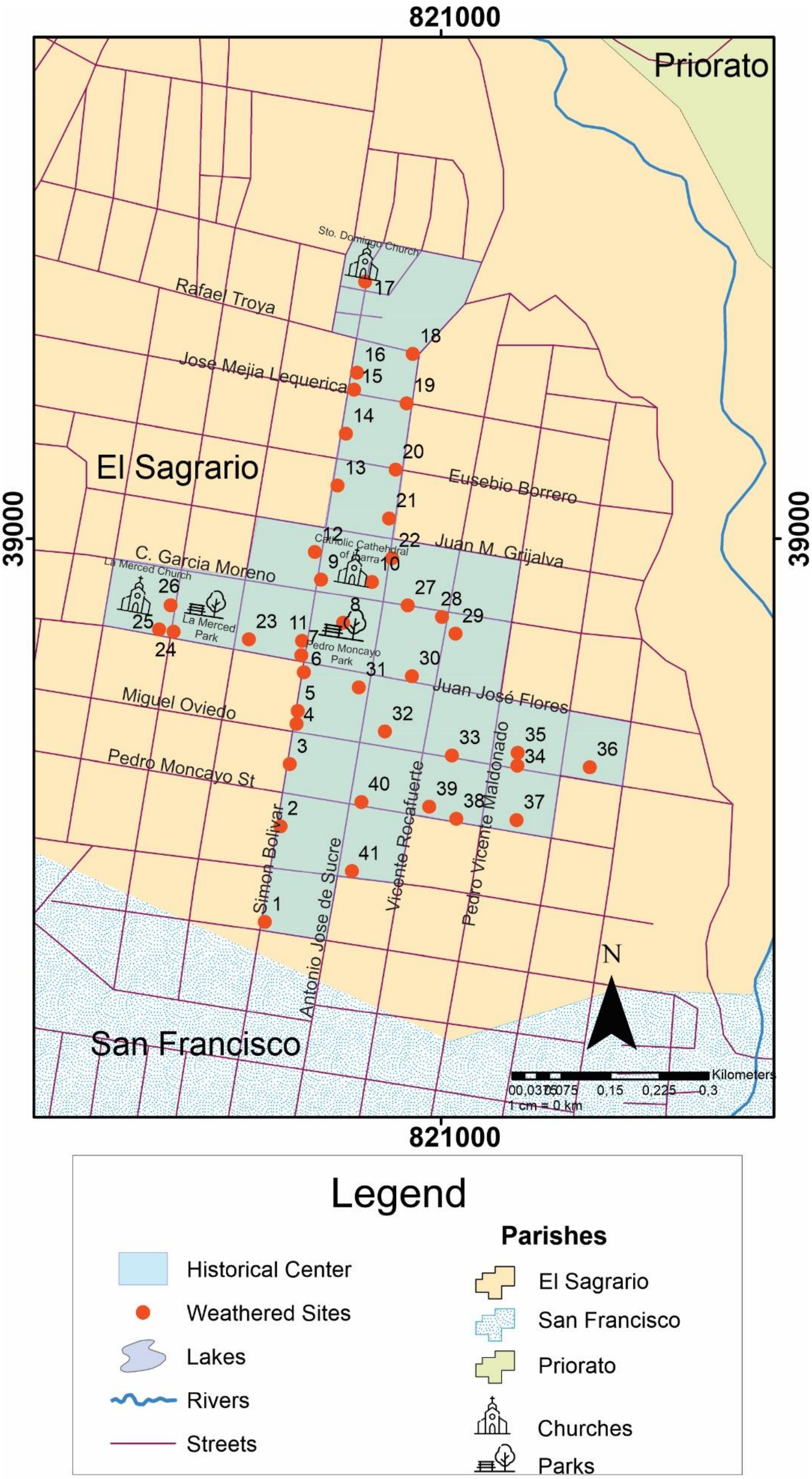


Figure 9. Map showing 41 points corresponding to weathering events along the historical center of Ibarra in the El Sagrario parish, including three historical churches, Santo Domingo, La Merced, and the Catholic center of Ibarra. Datum: WGS84.

The number of salt samples analyzed from each sector varied according to the amounts found in each of these sectors, with a total of 29 samples (Fig. 10). This analysis seeks to understand the relationship between the construction materials used and the growth of salt crystals (efflorescence), that cause the deterioration of structures in a wide variety of environments. The present study involved sampling efflorescence from various locations where such occurrences were observed. Samples were collected only if the extractable amount was sufficient for conducting X-ray diffraction (XRD) analysis. The XRD technique works with the principles stated in the Bragg’s law, which allows to predict the angles at which X-rays are diffracted by a material with periodic atomic structure (crystalline materials). The information obtained from those crystalline materials can be interpreted and exhibited as diffraction patterns. These last, behave as unique fingerprints for every mineral, that are compared to a database afterwards to obtain accurate approximations to the profiles of the minerals present in the samples (Sánchez et al., 2018). Nowadays, powder XRD is considered the most important tool in mineral exploration after empirical insight (Dinnebier & Billinge, 2008).

The samples were obtained between June and September 2022, mainly during dry and sunny weather. To minimize the potential influence of rain, sampling was avoided immediately after such events as they could potentially alter the composition or wash away salts. Moreover, the type of construction material from which each sample was taken was documented and considered in order to correlate the observed compounds with the age and construction type.

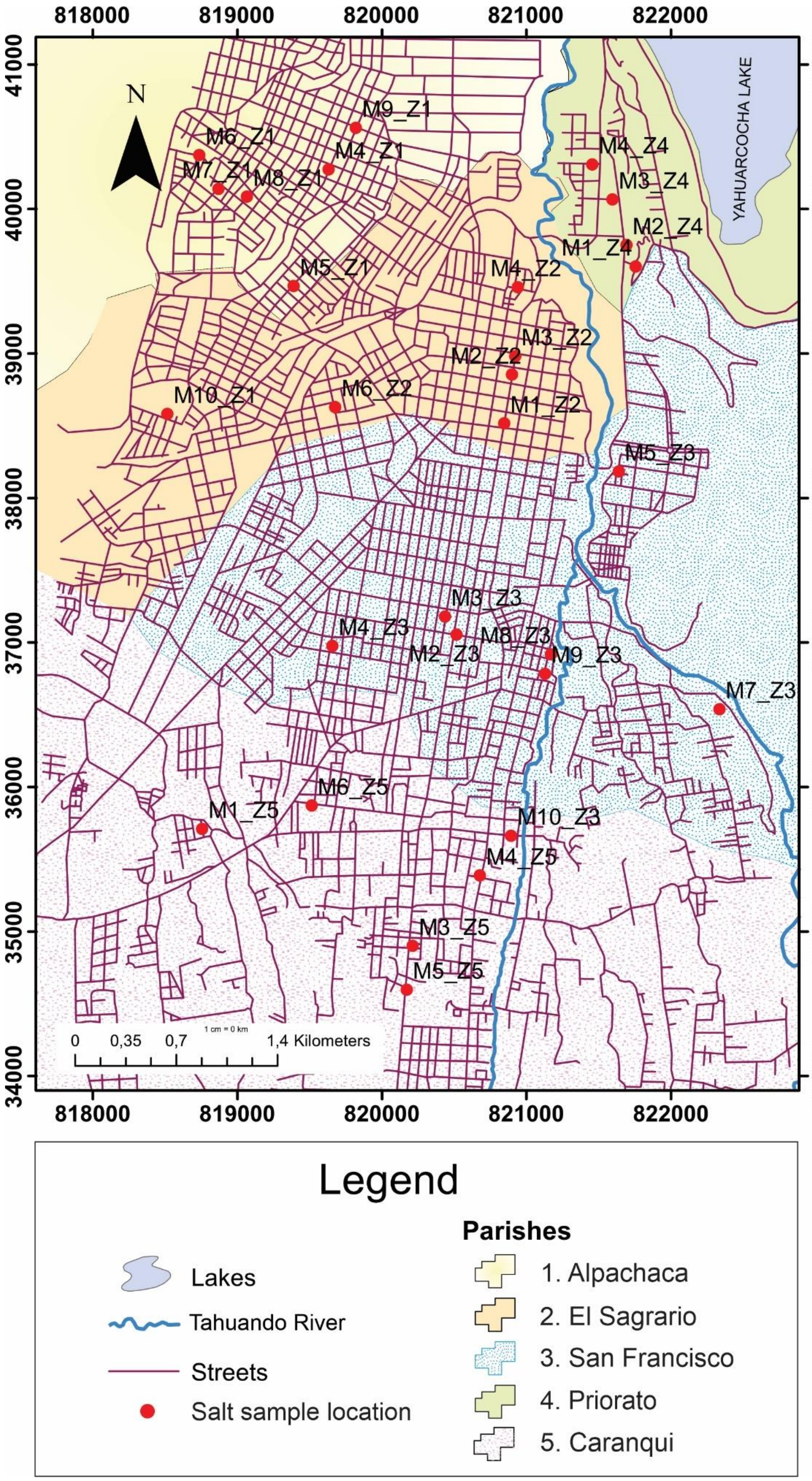
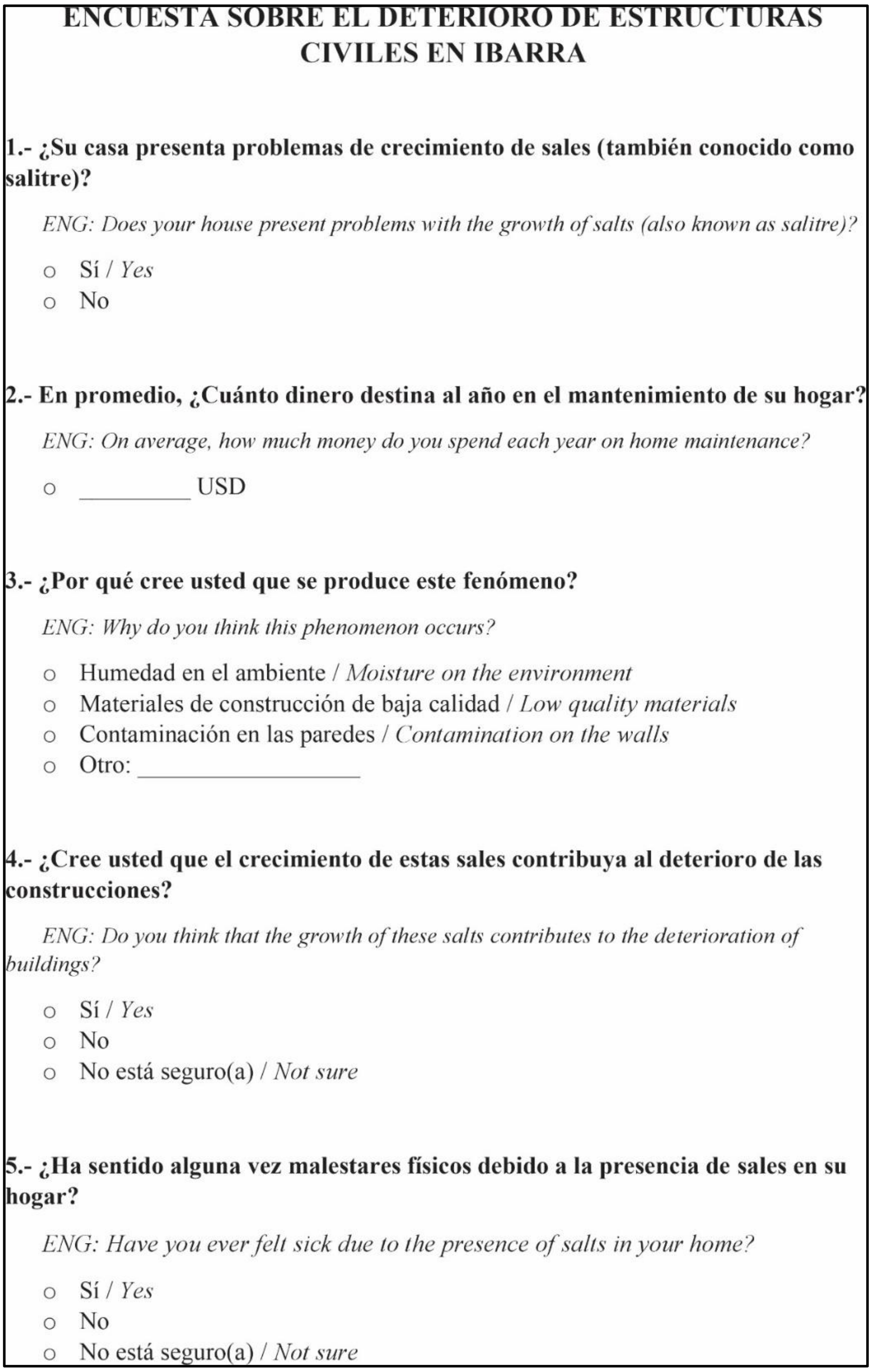


Figure 10. Map showing 29 points which correspond to efflorescence samples taken in the five urban parishes of Ibarra City. Datum: WGS84.

Furthermore, a survey in Spanish was conducted to ascertain the populace's comprehension of the decay caused by salt crystallization (refer to Fig. 11). The survey encompassed 159 individuals from the five urban districts of Ibarra city, enabling the comparison of the study findings with the extent of degradation reported by the residents of the researched areas.



ENCUESTA SOBRE EL DETERIORO DE ESTRUCTURAS CIVILES EN IBARRA

1.- ¿Su casa presenta problemas de crecimiento de sales (también conocido como salitre)?

ENG: Does your house present problems with the growth of salts (also known as salitre)?

○ Sí / *Yes*
○ No

2.- En promedio, ¿Cuánto dinero destina al año en el mantenimiento de su hogar?

ENG: On average, how much money do you spend each year on home maintenance?

○ _________ USD

3.- ¿Por qué cree usted que se produce este fenómeno?

ENG: Why do you think this phenomenon occurs?

○ Humedad en el ambiente / *Moisture on the environment*
○ Materiales de construcción de baja calidad / *Low quality materials*
○ Contaminación en las paredes / *Contamination on the walls*
○ Otro: __________________

4.- ¿Cree usted que el crecimiento de estas sales contribuya al deterioro de las construcciones?

ENG: Do you think that the growth of these salts contributes to the deterioration of buildings?

○ Sí / *Yes*
○ No
○ No está seguro(a) / *Not sure*

5.- ¿Ha sentido alguna vez malestares físicos debido a la presencia de sales en su hogar?

ENG: Have you ever felt sick due to the presence of salts in your home?

○ Sí / *Yes*
○ No
○ No está seguro(a) / *Not sure*

Figure 11. Survey applied to 159 people in Ibarra City.

4.1 Samples Preparation

Prior to the analysis of the saline growth samples, a total of 43 salt samples were collected. These were located at strategic points in the 5 parishes selected for the study. Small hermetically sealed bags and stainless-steel spatulas have been used for their collection and storage, considering that these should be handled carefully to avoid cross-contamination. The salts were selected, considering that these were light-colored minerals on the walls. Then, those considered of greater significance for our study were taken. The main parameter considered for this was the amount of salt taken in each bag, being the ones with more than 5 grams selected. In total, 29 sample bags were chosen for this analysis (Fig 12a).

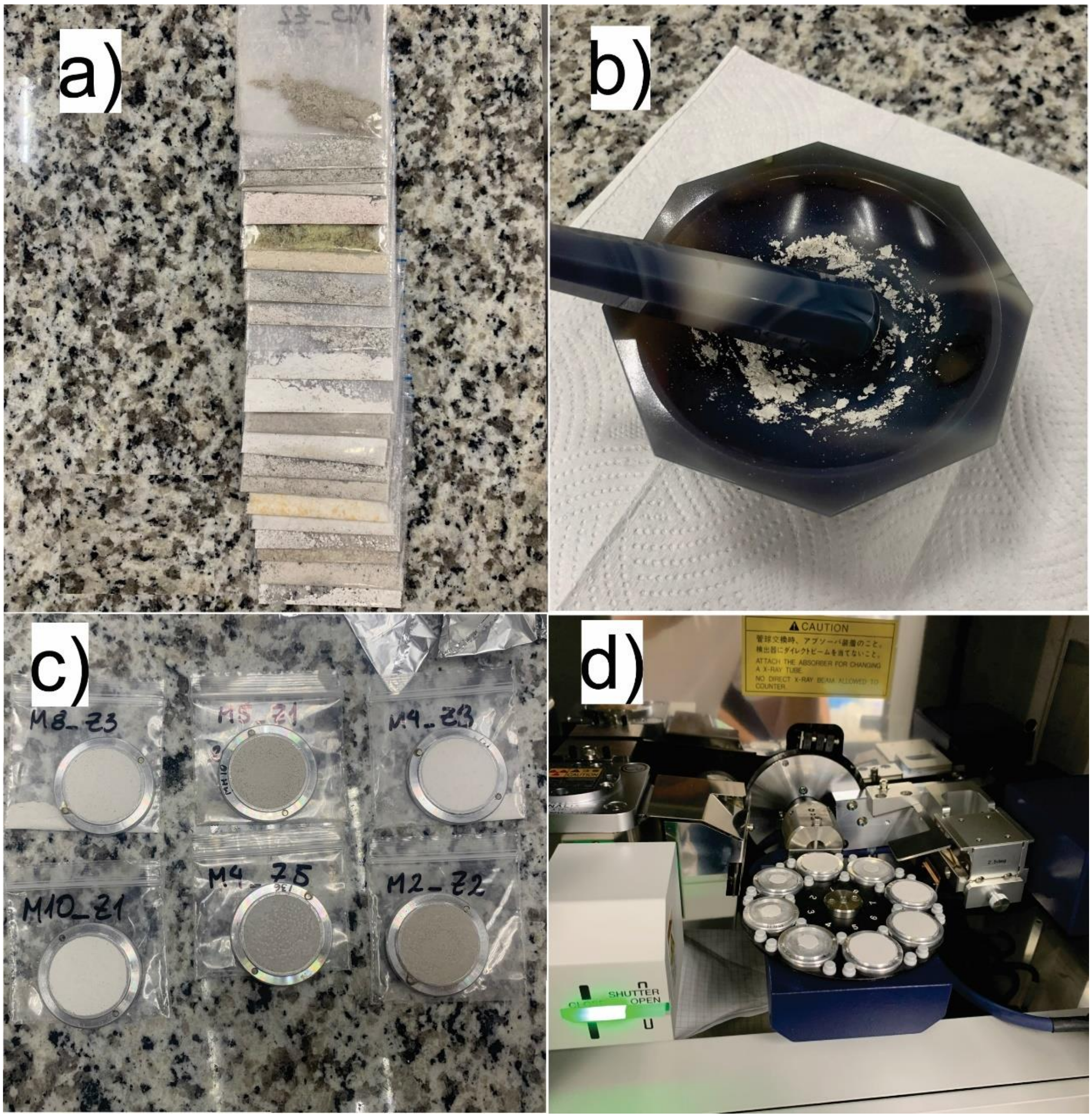


Figure 12. Sample preparation, a) Selection of samples, b) Pulverization of the samples, c) Salts prepared in the sample holders, d) Mounting of samples in the diffractometer.

The first step for sample preparation was to pulverize them using an agate mortar (Fig. 12b). After crushing, samples were placed in a new bag so they did not mix with any unpulverized residue from the original bag. Having all the pieces ready, we start to mount them in the sample holders, which have different sizes depending on the sample size. It is essential to check that the sample is well compacted to prevent it from spreading inside the diffractometer (Fig. 12c). The next step is to place the plates with the examples in the XDR, considering their order, and then leave them for approximately 40 minutes (Fig. 12d).

Although simple optical microscopy can be very helpful in characterizing sands and coarse silt-size crystals, powder XRD can be the most precise technique to analyze the mineralogy of finer-grained crystals. This method has become very prominent in the last decade because of its speed and ease of performance. Moreover, it requires a small amount of material, it is nondestructive, and can be applied to achieve semi-quantitative analyses of mineral mixers (Poppe et al., 2001).

We used the Rigaku Miniflex 600 X-Ray Diffractometer (Fig. 13), an advanced instrument with advantageous features like a variable temperature assembly and humidity chamber to perform the phase analysis of powdered salts. These features can help us expand the applications that can be performed, thus give us more information about the effect of temperature and humidity on the nature of material (Chauhan & Chauhan, 2014). The equipment used for this analysis has a D/tex Ultra 2 detector and an automatic 8-position sampler changer with a spinner. This diffractometer is connected to a computer that will give us a diffraction pattern (Annexes 2, 3, 4, 5, 6), with which we can obtain qualitative and quantitative information on the samples studied. This diffraction pattern plotted shows the intensity relationship against the angle of the detector 2θ as a diffractogram. The results obtained with the PXRD technique are expected to be close enough to the real minerals considering the non-invasive collection technique applied.

Figure 13. Powder X-Ray Diffractometer (Rigaku Miniflex 600) used for materials characterization. It has a two-dimensional detector and a Cu X-ray tube with a curved mirror for high-intensity X-ray beams, allowing for sensitive and high-quality data analysis.

When obtaining the diffraction patterns, the “Match!” software was applied to analyze them (Fig. 14). This program is useful for processing data obtained in the diffractometer since it allows us to analyze the patterns intuitively with the help of a database. The database with which the diffraction patterns were compared was PDF 2011. The steps with which the analysis of diffraction patterns was obtained accurately were the following:

1. Enter the raw data to the “Match!” program.
2. Smooth the data.
3. If the peak/average ratio is high, adjust the background to the base level of the pattern curves.
4. Subtract background.
5. Alpha2 stripping.

When the minerals present in each sample were accurately identified, they were added to a table where parishes separated them, this was to obtain an approximate idea of how the salts behave in different sectors of the city. This table included the sample code, the location in metric coordinates, the parish, the type of material from which it was taken, and finally the name of the mineral with its formula.

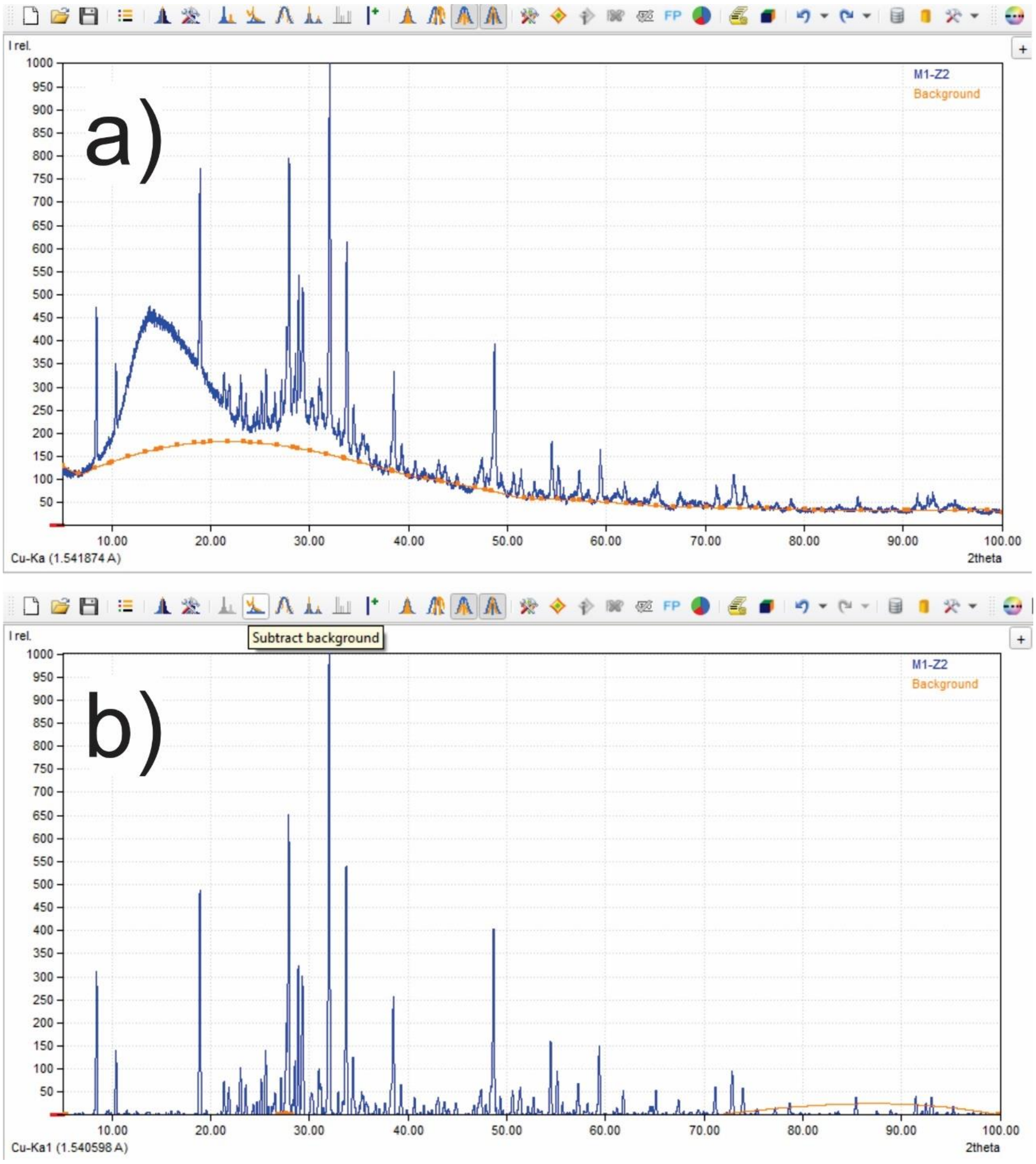


Figure 14. Before and after steps to process diffraction profiles were applied for phase identification. a) Raw data in Match!, b) Diffractogram showing the diffraction patterns of Thenardite, Darapskite and Calcite in a salt sample, obtained applying steps mentioned above.

5. RESULTS AND DISCUSSION

In this section, the investigation findings will be disclosed in detail, with which an attempt will be made to answer the initial questions of this work. The results were divided into two subheadings, which focus on the types of deterioration found, and the analysis of saline growth through the X-Ray Diffractometer.

5.1 Types of deterioration in Ibarra´s constructions

The city of Ibarra shows the occurrence of various types of deterioration, and this phenomenon is attributed to the region's geodynamics, which is influenced by volcanic activity and frequent seismic movements that are characteristic of the area. To investigate the types and extent of impairment present in Ibarra, a survey was conducted and classified according to the International Council on Monuments and Sites international classification system, which differentiates five primary categories of deterioration, including cracks, detachments, material loss, deposition of salts, and biological colonies.

The survey results were organized in a table format divided into four sections (Table 2). The left column displayed the Historical Center (HC) abbreviation, followed by the location where the different types of deterioration were identified. The second section includes the types of deterioration. The third section includes the level of weathering, which has been defined based on the observation of deterioration patterns from the bibliography. Lastly, it is crucial to know the type of material when studying types of deterioration because different materials have different properties and are susceptible to different kinds of deterioration. For example, masonry and concrete structures are porous and can be affected by efflorescence, while metal structures are susceptible to corrosion.

Based on the previously mentioned parameters, the following results were obtained from the survey in the historic center of the city of Ibarra:

Table 2. Table showing the types of deterioration found in each construction analyzed in the historical center of Ibarra city. See the location on Figure 11.

CODE	TYPE OF DETERIORATION					LEVEL OF WEATHERING	TYPE OF MATERIAL
	Crack	Detachment	Material loss	Deposit of salt	Biological colony		
HC-01			x			Low	Carved igneous rock
HC-02	x			x		Very low	Mixed igneous rock with concrete
HC-03		x	x			Low	Carved igneous rock
HC-04			x			Low	Carved igneous rock covered in lacquer
HC-05		x	x	x		Very low	Carved igneous rock
HC-06	x	x	x			High in concrete	Mixed igneous rock with concrete
HC-07	x		x	x	x	High	Carved igneous & sedimentary rocks
HC-08	x					Low	Carved igneous rock
HC-09		x	x	x		High	Mixed igneous rock with concrete
HC-10	x	x	x	x	x	Very high	Mixed igneous rock with concrete
HC-11	x	x		x		Medium	Concrete
HC-12	x			x		Low	Concrete
HC-13					x	Low	Carved igneous rock
HC-14			x	x		Medium	Carved sedimentary rock
HC-15	x	x		x		Medium	Concrete
HC-16				x		Very low	Sedimentary rock with concrete
HC-17			x			Low	Sedimentary rock (sandstone)
HC-18	x			x		Low	Concrete
HC-19		x	x		x	High	Mud and straw coated with concrete
HC-20			x	x		Low	Concrete
HC-21	x		x	x		Low	Concrete
HC-22	x		x	x		Medium	Concrete
HC-23		x	x			Low	Orange brick
HC-24			x			Low	Carved igneous rock
HC-25			x	x		Low	Concrete
HC-26			x			High in concrete	Carved igneous rock
HC-27	x		x			Medium	Carved igneous rock
HC-28	x	x		x		Low	Orange brick
HC-29			x			Low	Carved igneous rock
HC-30	x		x			Medium	Mixed igneous rock with concrete
HC-31				x		Low	Bricks and concrete
HC-32			x		x	Low	Carved igneous rock
HC-33	x		x	x		Medium	Carved sedimentary rock
HC-34	x		x			Medium	Bricks and concrete
HC-35			x			Low	Concrete
HC-36	x		x	x	x	High	Mixed igneous rock with concrete
HC-37			x			Low	Mixed igneous rock with concrete
HC-38				x		Low	Bricks and concrete
HC-39			x			High	Carved igneous rock
HC-40				x		Low	Bricks and concrete
HC-41			x	x		Medium	Concrete
TOTAL	17	10	29	22	6		

With this, we can determine that the most common type of deterioration in the city of Ibarra is produced by the loss of materials (29 samples, Table 2). One of the leading causes for this is seismic activity that can cause vibrations and movements in constructions, leading to further damage, especially in constructions made with volcanic materials that may have lower tensile strength. This phenomenon was present in all materials and, to a greater degree, in concrete and reworked sedimentary rock. It can be said that this type of deterioration could be a consequence of others since various factors, including physical, chemical, and biological processes, can produce it. Some common causes of material loss in construction include weathering, erosion, corrosion, and biological growth. In addition, efflorescence (22 samples, Table 2) could be observed as the second most common type of deterioration in Ibarra's buildings. When volcanic rocks are exposed to moisture, they can release mineral salts, which can migrate through porous materials like masonry and concrete. As the water evaporates, these salts can crystallize and create pressure within the material, leading to cracking and related damage. Efflorescence was more common in structures made of concrete, although it was also observed with remarkable recurrence in bricks (masonry) (Fig. 7b). It was also possible to notice a large construction made of mud and straw, which presented a very high degree of erosion, much greater than that described in concrete.

In general terms, it was observed that the constructions built with reworked igneous rock on their façade reported a lower level of deterioration compared to those made of other materials, such as concrete or masonry. However, these materials also come from volcanic sources, especially in regions where they are abundant, due to their desirable properties such as strength, durability, and insulation. Based on the properties of volcanic materials and how they behave in nature, it can be said that these can pose a risk for deterioration due to their chemical and physical properties.

One way volcanic materials can lead to deterioration is through their susceptibility to weathering and erosion. Volcanic rocks are often porous and can absorb water, which can cause the material to expand and contract as the water freezes and thaws, leading to cracking and other damage. This can be particularly problematic in regions with significant temperature fluctuations or with frequent precipitation. Another way in which volcanic materials can contribute to deterioration is by releasing salts through their porous structure, particularly when combined with other materials that possess a high salt content.

Moreover, volcanic materials can also contain certain minerals that are corrosive to metals. For example, sulfur is often found in volcanic rocks and can lead to the formation of sulfuric acid when it meets water and oxygen. This acid can corrode metal components in buildings and structures, weakening and failing the outer structure of these.

5.2 Deterioration associated with Efflorescence

Efflorescence is a common phenomenon in environments with high humidity or moisture, where there is water present to dissolve the salts and transport them to the surface (Longhi et al., 2019). The most common materials where we can find them are concrete, brick, masonry, stucco, and natural stones. Since efflorescence can occur in any environment where moisture and water-soluble salts are present, and it is important to address the underlying moisture issue to prevent further damage to building materials.

To understand the efflorescence issue in Ibarra, a survey was conducted on 159 households. The survey was divided among the five urban parishes included in this study. Even though the sample corresponds to only 0.43% of the total number of households, it is considered representative as it was taken from individuals from all social strata of Ibarra City. It should be noted that 100% of the households surveyed were found to be living in houses constructed with igneous materials such as cement, masonry, and concrete blocks.

5.2.1 Surveys and statistics

According to the surveys in Ibarra City (see Fig. 15), 83% of the people have stated that their homes show some salt weathering (efflorescence). This corresponds to both inside and outside of their houses. This type of deterioration has caused annual maintenance losses amounting to $131 U.S. Dollars per household in the city, corresponding to 31**%** of the basic monthly salary. Putting this in perspective, annual expenses on maintenance and repairs of homes in the city of Ibarra amount to approximately 4,843,856 USD. Despite the concern and attempts of people to mitigate this phenomenon, there are very few options for it other than avoiding the implementation of low-quality cements, reducing the water ratio when mixing concrete, or the isolation of walls and floors using hydrophobic coating, which can cause additional expenses in the construction of buildings.

Moreover, 68% of people believe salt deterioration is due to humidity. Although the other reasons for possible deterioration remain low, 19% of the population thinks salt deterioration is due to the low quality of the materials used in construction. Considering the bibliography consulted, both reasons can be considered valid. This is due to the high amount of sulfates, carbonates and nitrates that are unconsciously used in cement and stone material. We also know that humidity, together with the constant increase in temperature, is one of the triggering mechanisms in the crystallization of salts.

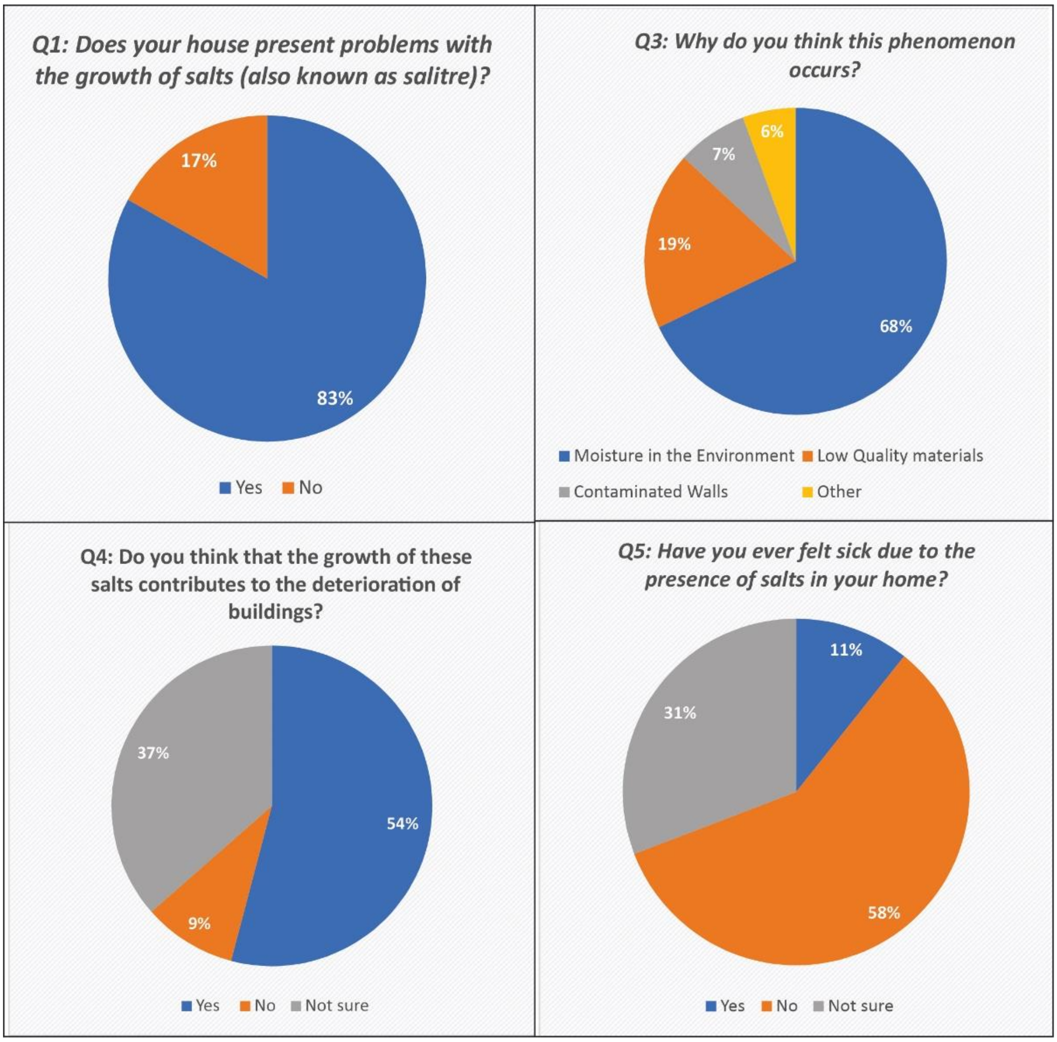


Figure 15. Results of 4 of the 5 questions from the survey about salt weathering carried out to 159 individuals living in particular residences, showing the incidence of salt weathering as a common problem in Ibarra City.

One of the most shocking data in this study is that only 54% of the population is familiar with the harmful effects of salt growth in buildings (Fig. 15Q4). On the other hand, 37% are not sure of the damage that this entails, this may be because the rate of deterioration due to saline growth may be relatively low. Salts do not present a major risk to the population's health in general, since only 11% have reported having felt any symptoms related to salt exposure. In general terms, the population is moderately educated on this problem. However, most of them are exposed to these types of deterioration daily.

5.2.2 X-Ray Diffraction Results

Table 3 shows the results of the 29 salt samples analyzed, which were identified using the X-Ray Diffraction (XRD) technique. These results show the different minerals present in each sample, at the same time, we can observe the place of deposition of these. The semi-quantitative values are not shown in this case due to the uncertainty that exists in them. According to the mineral occurrence graph (Fig. 17), we can see that the most common group of salts in the samples is sulfates, a group of minerals that can not only bring aesthetic concerns but can also lead to structural damage over time. In addition, other groups of minerals, such as nitrates, carbonates, borates, and silicates, were also present in the samples.

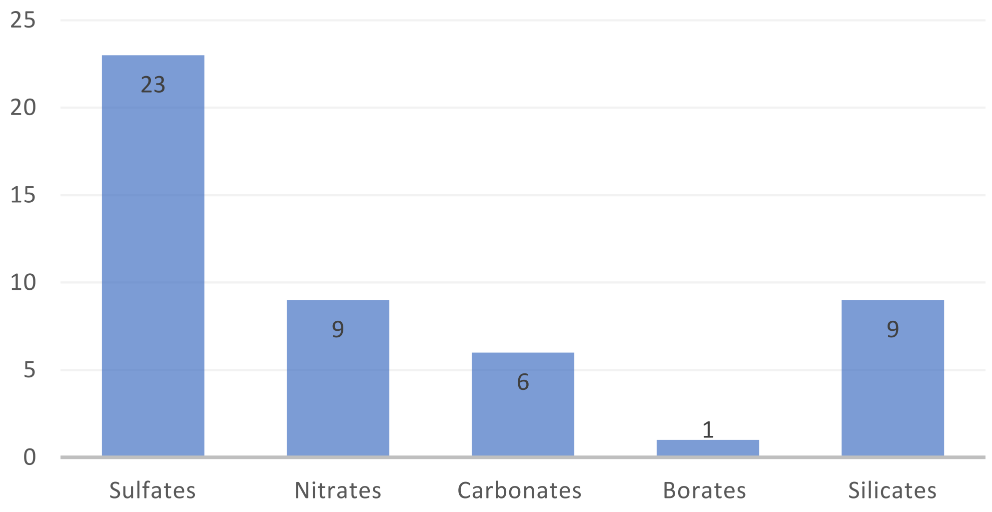


Figure 17. Number of ions of salts that showed dominance in the 29 salt samples studied after being analyzed using the Powder XRD technique. Some samples showed minerals that fall in more than one ion, (e.g. Darapskite $Na_3(SO_4)(NO_3)\cdot H_2O$, being both a sulfate and a nitrate)

Table 3. Mineral phases present in 29 salt samples using Powder XDR technique. X, Y correspond to the metric coordinates where they were found. The code was made based on the number of the sample, followed by the zone in which this was found (Muestra'x'_Zone'x').

CODE	X	Y	PARISH	PLACE OF DEPOSITION	MINERALS
M4_Z1	819629,65	40272,34	Azaya	Concrete	Thenardite (Na2SO4) Anorthite (Al2CaO8Si2)
M5_Z1	819388,25	39465,26		Concrete	Nitratine (NaNO3)
M6_Z1	818734,98	40371,55		Concrete	Thenardite (Na2SO4) Calcite (CCaO3)
M7_Z1	818867,74	40139,08		Concrete	Thenardite (Na2SO4)
M8_Z1	819065,18	40084,25		Concrete	Thenardite (Na2SO4) Albite (Na(Si3Al)O8)
M9_Z1	819818,30	40561,25		Concrete	Thenardite (Na2SO4) Gypsum (CaSO4*2H2O)
M10_Z1	818513,82	38580,86		Concrete	Thenardite (Na2SO4) Darapskite (Na3(NO3)(SO4)
M1_Z2	820844,62	38514,83	El Sagrario	Concrete	Thenardite (Na2SO4) Darapskite (Na3(NO3)(SO4) Calcite (CCaO3)
M2_Z2	820899,44	38852,84		Carved Basalt	Calcite (CCaO3) Andesine
M3_Z2	820922,35	38980,34		Mix igneous carved rocks with concrete	Thenardite (Na2SO4) Gowerite
M4_Z2	820939,14	39458,36		Concrete	Thenardite (Na2SO4) Gypsum (CaSO4*2H2O)
M6_Z2	819675,44	38627,69		Concrete	Nitratine (NaNO3)
M2_Z3	820515,84	37054,28	San Francisco	Concrete	Thenardite (Na2SO4) Labradorite
M3_Z3	820436,61	37178,42		Concrete	Nitratine (NaNO3)
M4_Z3	819656,55	36974,84		Concrete	Nitratine (NaNO3)
M5_Z3	821637,44	38182,95		Concrete	Thenardite (Na2SO4) Gypsum (CaSO4*2H2O) Albite (Na(Si3Al)O8)
M7_Z3	822334,14	36537,43		Concrete	Thenardite (Na2SO4) Darapskite (Na3(NO3)(SO4)
M8_Z3	821168,76	36917,84		Concrete	Nitratine (NaNO3)
M9_Z3	821127,57	36782,91		Concrete	Thenardite (Na2SO4) Anorthite ((Ca,Na)(Si,Al)4*O8) Calcite (CCaO3)
M10_Z3	820892,54	35662,15		Concrete	Thenardite (Na2SO4) Calcite (CCaO3)
M1_Z4	821755,10	39601,02	Priorato	Concrete	Thenardite (Na2SO4)
M2_Z4	821691,10	39749,75		Concrete	Thenardite (Na2SO4)
M3_Z4	821593,85	40064,47		Concrete	Thenardite (Na2SO4)
M4_Z4	821454,28	40307,46		Concrete	Thenardite (Na2SO4) Georgeyite (K2SO4(CaSO4)*5H2O)
M1_Z5	818754,82	35709,09	Caranqui	Concrete	Thenardite (Na2SO4) Darapskite (Na3(NO3)(SO4)
M3_Z5	820212,06	34898,72		Orange Brick	Thenardite (Na2SO4) Albite (Na(Si3Al)O8)
M4_Z5	820676,74	35386,67		Concrete with pebbles	Thenardite (Na2SO4) Albite (Na(Si3Al)O8) Cristobalite low (SiO2)
M5_Z5	820170,58	34596,23		Concrete	Thenardite (Na2SO4)
M6_Z5	819512,77	35870,30		Concrete	Labradorite ((Ca,Na)(Al1,6Si2,4O8)) Thenardite (Na2SO4) Calcite (CCaO3)

5.2.2.1 Sulfates

Sulfate salts can be found in various building materials, but they are more commonly present in materials made with cement, such as concrete, mortar, and stucco. This sulfate efflorescence occurs because cement is made with calcium sulfate as one of its main components. In addition to calcium sulfate, other sulfate salts such as sodium sulfate and magnesium sulfate can also be present in these materials due to the use of water or aggregates containing these salts (Andrade Neto et al., 2021). Sulfates can enter building materials through various means, such as groundwater or the mixing water used to make concrete. When water infiltrates the building material, it dissolves the sulfates and carries them to the surface. As the water evaporates, the sulfates crystallize, leaving behind a powdery, white residue.

Sulfates are particularly problematic because they can cause significant damage to the building material. They can react with the calcium hydroxide present in cement and form calcium sulfate, which has a larger volume than the original salts. This can cause cracking and spalling of the building material, leading to structural damage (Liu et al., 2014). To prevent sulfates from causing efflorescence, it is vital to use building materials that are low in sulfates or to limit the exposure of the material to water. Proper waterproofing and drainage systems can also help prevent water infiltration into the building material.

These are the most common minerals found in the samples, being present in 23 of them. This corresponds to 79% of the analyzed samples. Sulfates are mainly associated with concrete and the zones that presented this mineral in greater quantity were zones 5 and 1. The most common mineral here is thenardite, a sodium sulfate.

In both zone 1 and zone 4, thenardite (Na_2SO_4) was present in all the samples. However, in zone 4, three samples exclusively contained this mineral. It is believed that this could be due to the high humidity in the environment, which caused other more soluble minerals to be washed away from the samples, leaving only sodium sulfate behind. Along with thenardite, two different minerals, darapskite ($Na_3(NO_3)(SO_4)$) and gypsum ($CaSO_4*2H_2O$), were also found in these zones. In addition, georgeyite ($K_2SO_4(CaSO_4)*5H_2O$) was found in only one sample in zone 4.

Table 4. Sulfate minerals found in 23 samples with their description, formula, crystal system, and place of deposition.

SULFATES

Sample		Mineral	Formula	Crystal System	Place of deposition
M4_Z1	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
M6_Z1	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
M7_Z1	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
M8_Z1	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
M9_Z1	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
	Calcium sulfate hydrate	Gypsum	CaSO4*2H2O	Monoclinic	
M10_Z1	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
	Sodium nitrate sulfate	Darapskite	Na3(NO3)(SO4)	Monoclinic	
M1_Z2	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
	Sodium nitrate sulfate	Darapskite	Na3(NO3)(SO4)	Monoclinic	
M3_Z2	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete & igneous rocks
M4_Z2	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
	Calcium sulfate hydrate	Gypsum	CaSO4*2H2O	Monoclinic	
M2_Z3	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
M5_Z3	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
	Calcium sulfate hydrate	Gypsum	CaSO4*2H2O	Monoclinic	
M7_Z3	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
	Sodium nitrate sulfate	Darapskite	Na3(NO3)(SO4)	Monoclinic	
M9_Z3	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
M10_Z3	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
M1_Z4	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
M2_Z4	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
M3_Z4	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
M4_Z4	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
	Calcium potassium sulfate	Goergeyite	K2SO4(CaSO4)*5H2O	Monoclinic	
M1_Z5	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
	Sodium nitrate sulfate	Darapskite	Na3(NO3)(SO4)	Monoclinic	
M3_Z5	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Orange Brick
M4_Z5	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concre and pebbles
M5_Z5	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete
M6_Z5	Sodium sulfate	Thenardite	Na2SO4	Orthorhombic	Concrete

Although the presence of sulfates in construction materials can be very dangerous for civil structures, effective remediation methods exist to address this issue. According to (Neville, 2004), concretes with meager amounts of sulfates can be extracted easily using a dissolution method with a low water-to-cement ratio (w/cm). When the amounts of soluble sulfate are low, an effective way to mitigate it could be the double application of limo. However, (Haynes & Bassuoni, 2011), stated that using a low w/c can increase the proportion of pores, which can be disadvantageous for salt growth and even though it can make concrete more resistant to salt weathering, it does not make it immune.

5.2.2.2 Carbonates

Carbonates can play a role in efflorescence when they are present in building materials such as concrete, brick, or stone. Carbonates are compounds that can grow at moist places like caves, hot springs, and hydrothermal vents and are commonly found in materials that contain limestone or other forms of calcium carbonate ($CaCO_3$) (Nord, 1992). When water infiltrates building materials containing carbonates, it dissolves them and forms a weak carbonic acid solution. This solution can react with other minerals in the building material, such as calcium hydroxide, to create new salts that are more water-soluble than the original minerals. These new salts can then be carried to the surface of the building material by water, where they crystallize and form efflorescence.

Efflorescence caused by carbonates is typically white or gray in color and can be difficult to remove. Unlike sulfates, carbonates are not as damaging to the building material itself and are not likely to cause structural damage (Dow & Glasser, 2003). However, efflorescence can be unsightly and indicate excess moisture in the building material, which can lead to other forms of damage, such as cracking or spalling. To prevent efflorescence caused by carbonates, it is important to minimize the exposure of building materials to water and use materials low in carbonates. Proper installation and maintenance of waterproofing and drainage systems can also help prevent water infiltration into the building material. If efflorescence does occur, it can be removed using a variety of methods such as pressure washing or chemical cleaning.

Carbonates were found in less quantity than sulfates. However, these have also been cited as one of the main causes of efflorescence. A total of six samples containing carbonates have been found. The only mineral that has been identified in this group is calcite, a calcium carbonate. Most of these samples were taken in concrete (5), while only one corresponds to reworked basalt.

Table 5. Carbonate minerals found in 6 samples in zones 1, 3 and 5, with their description, formula, crystal system, and place of deposition.

CARBONATES

Sample		Mineral	Formula	Crystal System	Place of deposition
M6_Z1	Calcium carbonate	Calcite	CCaO3	Rhombohedral	Concrete
M1_Z2	Calcium carbonate	Calcite	CCaO3	Rhombohedral	Concrete
M2_Z2	Calcium carbonate	Calcite	CCaO3	Rhombohedral	Carved basalt
M9_Z3	Calcium carbonate	Calcite	CCaO3	Rhombohedral	Concrete
M10_Z3	Calcium carbonate	Calcite	CCaO3	Rhombohedral	Concrete
M6_Z5	Calcium carbonate	Calcite	CCaO3	Rhombohedral	Concrete

5.2.2.3 Nitrates

Nitrates can contribute to efflorescence when they are present in building materials such as concrete, brick, or stone. Nitrates contain nitrate (NO_3) and are commonly found in fertilizers and animal waste (Laue et al., 1914). When nitrates are present in building materials, they can react with other minerals to form water-soluble salts (Nord, 1992). These salts can then be carried to the surface of the building material by water, where they crystallize and form efflorescence.

Efflorescence caused by nitrates is typically yellow or brown in color and can be difficult to remove. Like carbonates, nitrates are not as damaging to the building material itself as sulfates, but they can indicate the presence of excess moisture in the material, which can lead to other forms of damage. To prevent efflorescence caused by nitrates, it is important to limit the exposure of building materials to nitrogen sources, such as fertilizers or animal waste. Proper installation and maintenance of waterproofing and drainage systems can also help prevent water infiltration into the building material. If efflorescence caused by nitrates does occur, it can be removed using various methods such as pressure washing or chemical cleaning. However, it is essential to address the underlying cause of the efflorescence to prevent it from recurring in the future.

Table 6. Nitrate minerals found in 6 samples in zones 1, 3 and 5, with their description, formula, crystal system, and place of deposition

NITRATES

Sample		Mineral	Formula	Crystal System	Place of deposition
M5_Z1	Sodium nitrate	Nitratine	NaNO3	Rhombohedral	Concrete
M10_Z1	Sodium nitrate sulfate	Darapskite	Na3(NO3)(SO4)	Monoclinic	Concrete
M1_Z2	Sodium nitrate sulfate	Darapskite	Na3(NO3)(SO4)	Monoclinic	Concrete
M6_Z2	Sodium nitrate	Nitratine	NaNO3	Rhombohedral	Concrete
M3_Z3	Sodium nitrate	Nitratine	NaNO3	Rhombohedral	Concrete
M4_Z3	Sodium nitrate	Nitratine	NaNO3	Rhombohedral	Concrete
M7_Z3	Sodium nitrate sulfate	Darapskite	Na3(NO3)(SO4)	Monoclinic	Concrete
M8_Z3	Sodium nitrate	Nitratine	NaNO3	Rhombohedral	Concrete
M1_Z5	Sodium nitrate sulfate	Darapskite	Na3(NO3)(SO4)	Monoclinic	Concrete

Nitrates have been the second most common group found in the samples (Table 6). Deterioration by nitrate salts is considered less aggressive than the previous ones. However, this can also affect the aesthetics of buildings and destroy layers of paint. Only two minerals have been found in this group, which are nitratine ($NaNO_3$) and darapskite ($Na_3(NO_3)(SO_4)$). In the case of darapskite, this is a sodium nitrate sulfate, which is why it has also been previously included in the group of sulfates.

5.2.2.4 Borates

Borates are not as common in efflorescence as sulfates, carbonates, or nitrates (Table 7). Borates contain the borate ion (BO_3) and are commonly used as preservatives in wood and other materials (Fogel & Lloyd, 2002). While borates can contribute to the formation of efflorescence under certain conditions, such as when they are present in wood or other materials that are in contact with moisture, they are not typically a primary cause of efflorescence in building materials such as concrete, brick, or stone.

Depending on the specific borate compound present, efflorescence caused by borates can be white, yellow, or brown. If efflorescence caused by borates does occur, it can be removed using various methods such as pressure washing or chemical cleaning. To prevent the formation of efflorescence caused by borates, it is important to limit the exposure of materials to borate-containing preservatives and to use materials that are low in borates, if possible. Proper installation and maintenance of waterproofing and drainage systems can also help prevent water infiltration into the building material, which can exacerbate efflorescence caused by borates.

Table 7. Borate minerals found in the samples

BORATES

Sample		Mineral	Formula	Crystal System	Place of deposition
M3_Z2	Calcium Hydroxide Borate Hydrate	Gowerite	Ca[B5O8(OH)][B(OH)3]·3H2O	Monoclinic	Concrete & igneous rocks

Borates are very rare in this context. Even so, the presence of the mineral gowerite ($Ca[B_5O_8(OH)][B(OH)_3]\cdot 3H_2O$) has been found in one of the samples. This corresponds to the zone 2.

5.2.5 Silicates

Silicates are generally not responsible for efflorescence in building materials since they are insoluble in water (Longhi et al., 2019). However, there are some rare cases where silicates can contribute to efflorescence. For example, if a building material contains a small amount of soluble silicate, such as sodium silicate, it can react with other compounds in the material to form water-soluble salts that can then be transported to the surface and form efflorescence (Longhi et al., 2019).

Silicates are compounds that contain the silicate ion (SiO_4) and are commonly found in materials such as sand, glass, and ceramics. These materials are of volcanic origin and efflorescence caused by silicates is typically white or gray, but it is relatively rare and not commonly encountered in building materials (Veinot et al., 1991). If efflorescence caused by silicates does occur, it can be removed using a variety of methods such as pressure washing or chemical cleaning.

Table 8. Silicate minerals found in 9 samples. These are present in Zones 1, 2, 3, 5.

SILICATES

Sample		Mineral	Formula	Place of deposition
M4_Z1	Sodium calcium aluminum silicate	Anorthite	Al2CaO8Si2	Concrete
M8_Z1	Sodium aluminum silicate	Albite	Na(Si3Al)O8	Concrete
M2_Z2	-	Andesine	(Na,Ca)[Al(Si,Al)Si2O8]	Carved basalt
M2_Z3	-	Labradorite	(Ca,Na)[Al(Al,Si)Si2O8]	Concrete
M5_Z3	Sodium aluminum silicate	Albite	Na(Si3Al)O8	Concrete
M9_Z3	Sodium calcium aluminum silicate	Anorthite	Al2CaO8Si2	Concrete
M3_Z5	Sodium aluminum silicate	Albite	Na(Si3Al)O8	Orange brick
M4_Z5	Sodium aluminum silicate	Albite	Na(Si3Al)O8	Concre and pebbles
M6_Z5	-	Labradorite	(Ca,Na)[Al(Al,Si)Si2O8]	Concrete

Silicates, likewise nitrates, are found after sulfates as the most common group in the samples (Table 8). The only zone that did not present silicate growth was Zone 4. The minerals found in this group are albite (4), anorthite (2), labradorite (2) and andesine (1), all sodium silicates proceeding from igneous rocks.

6. CONCLUSIONS AND RECOMMENDATIONS

In summary, the most common type of deterioration observed in Ibarra is material loss, which is a natural result of the aging of structures and can also lead to other forms of deterioration, such as cracks and detachment. Mud and straw constructions, followed by concrete and brick, exhibited the greatest material loss. However, constructions made out of concrete showed the most cases of cracks and fractures. These structures were primarily used for residential and commercial purposes. The degree of material loss was more significant in older constructions, except for churches and historical buildings whose primary construction material was carved volcanic rocks like andesite or basalt.

The second most common type of weathering observed was the growth of salts, which occurred on the facades of 54% of the documented sites. Surprisingly, the growth of salts was more frequently observed in constructions with a modern appearance, unlike the material loss, which was more common in older constructions.

It should be noted that the observations made in this study were based on the historic center of Ibarra, and it was assumed that similar types of weathering would be present throughout the city since it has a variety of building types. However, outside of the historic center, there are a greater number of buildings with concrete facades, which suggests that the type of deterioration associated with concrete may be more common outside the historic center than within it. Specifically, the study found that salt deterioration is much more prevalent outside of the historic center.

On the other hand, the historic center of Ibarra has a significant number of buildings made using igneous rock as raw material, and these structures exhibited lower levels of efflorescence compared to other areas of the city. It is important to note that this study only provides a snapshot of the state of weathering and deterioration in Ibarra and that further research may be needed to fully understand the scope and extent of deterioration in the city.

Efflorescence was observed in many sites whose main material was concrete. With this, it can be inferred that high efflorescence is linked to the use of fine volcanic materials (ash, tuff, etc.), which are the main components in Ibarra’s cement. Also, it is presumed that these cements were enriched with evaporites, which makes them more prone to present salt growth. The most abundant mineral in the analyzed samples was thenardite (Na_2SO_4), which is part of the sulfate functional group. This was present in 79% of the total samples taken (23 samples). For those samples whose color was lighter, that is, the ones that were less contaminated, a single mineral could be observed present. This varied between nitratine ($NaNO_3$), thenardite (Na_2SO_4) and calcite ($CCaO_3$). About the samples that were taken inside of buildings (4), three of them corresponded to the mineral nitratine and one of them was calcite. These results can suggest that it is more likely to find the mineral nitratine indoors, which coincides with its hygroscopic nature.

One way to reduce sulfate crystallization in concrete is to reduce the water-to-cement (w/c) ratio. This reduces the dampness on the structure, restraining the movement of sulfates to the exterior. To evade any type of salt deterioration, constructions, where porous materials are used, should be avoided near places with high humidity levels. The main mitigation measure is prevention through the physical separation of construction materials by means of a barrier that prevents their contact with damped soil.

In response to the study's main objective, it was found that the deterioration of structures in Ibarra is primarily related to the use of construction materials with high salt content and fine pyroclastic materials like tuff and ashes. These materials are mostly obtained from local sources, primarily igneous deposits from the "Volcánicos de Imbabura" lithological unit. Furthermore, it was also found that the use of carved igneous rock in buildings over a hundred years old has proven to be effective against deterioration in Ibarra, exhibiting the lowest levels of deterioration among all materials. However, these structures may still experience a low-level deterioration over time due to alveolarization.

While the use of materials of volcanic origin is one of the main causes for deterioration in Ibarra City, its climatological conditions can contribute to a huge extent to this issue. It is known that volcanic ash and other fine pyroclastic materials can be highly porous, this can be translated to a higher moisture absorption and retention, which can also contribute to the dissolution and mitigation of salts. Another property of fine pyroclastic materials is their abrasive effect and its easiness to erode when it is found in high concentrations.

7. BIBLIOGRAPHY

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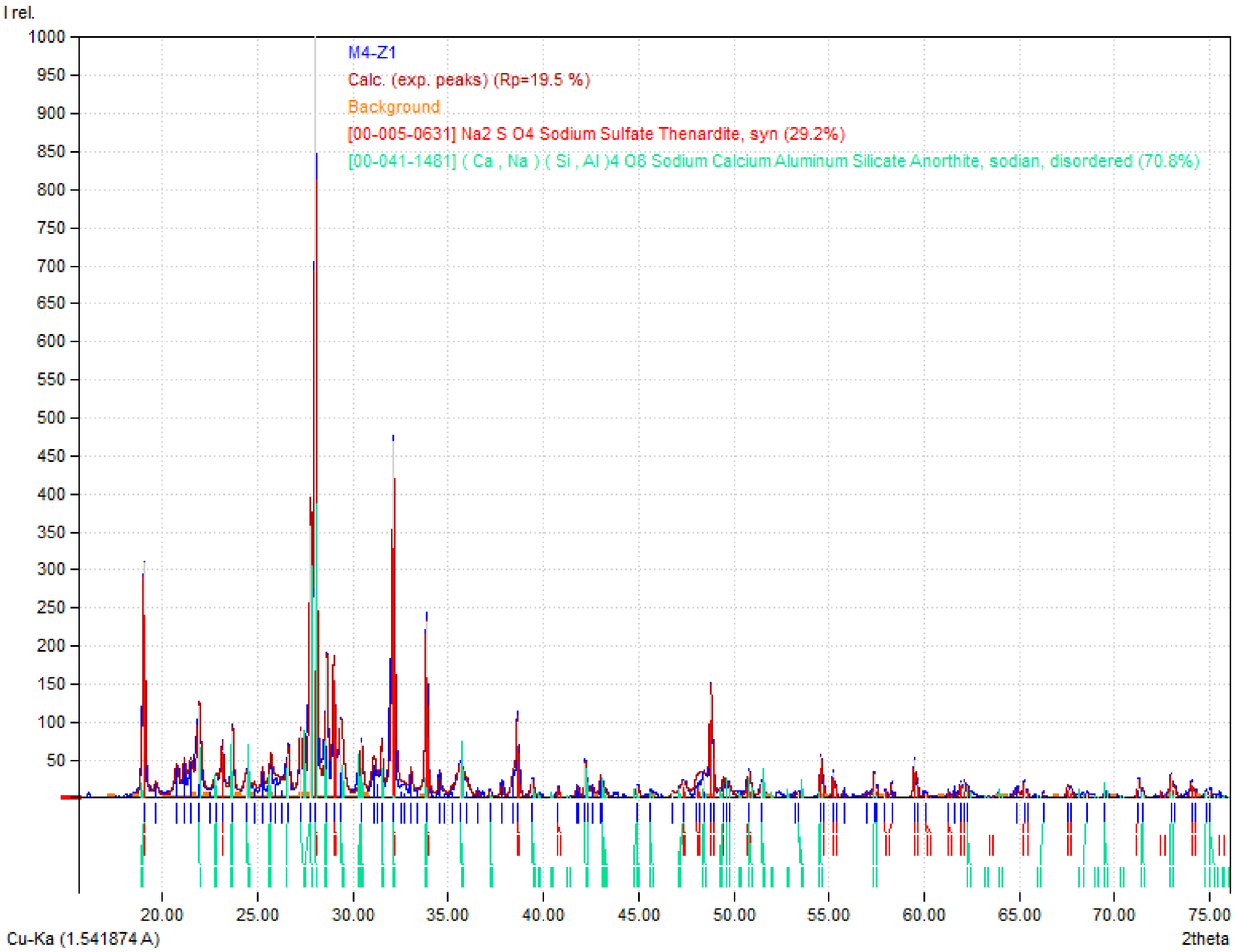
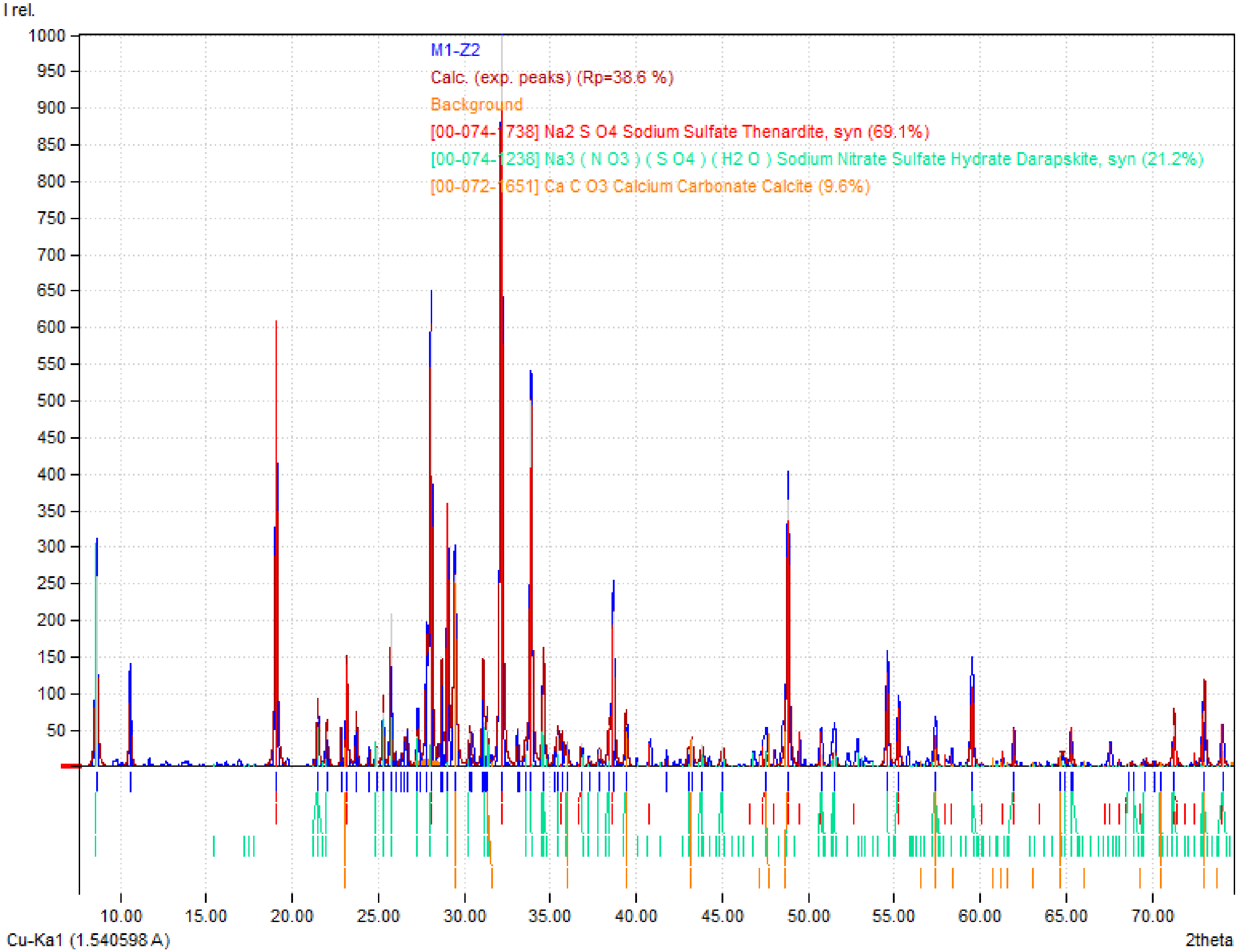
8. ANNEXES

1. Survey carried out on the outside of buildings in the Historical Center of Ibarra. This table includes the code corresponding to the area (Historic Center) and the number of the site, along with the X, Y metric coordinates and the place where every spot was located.

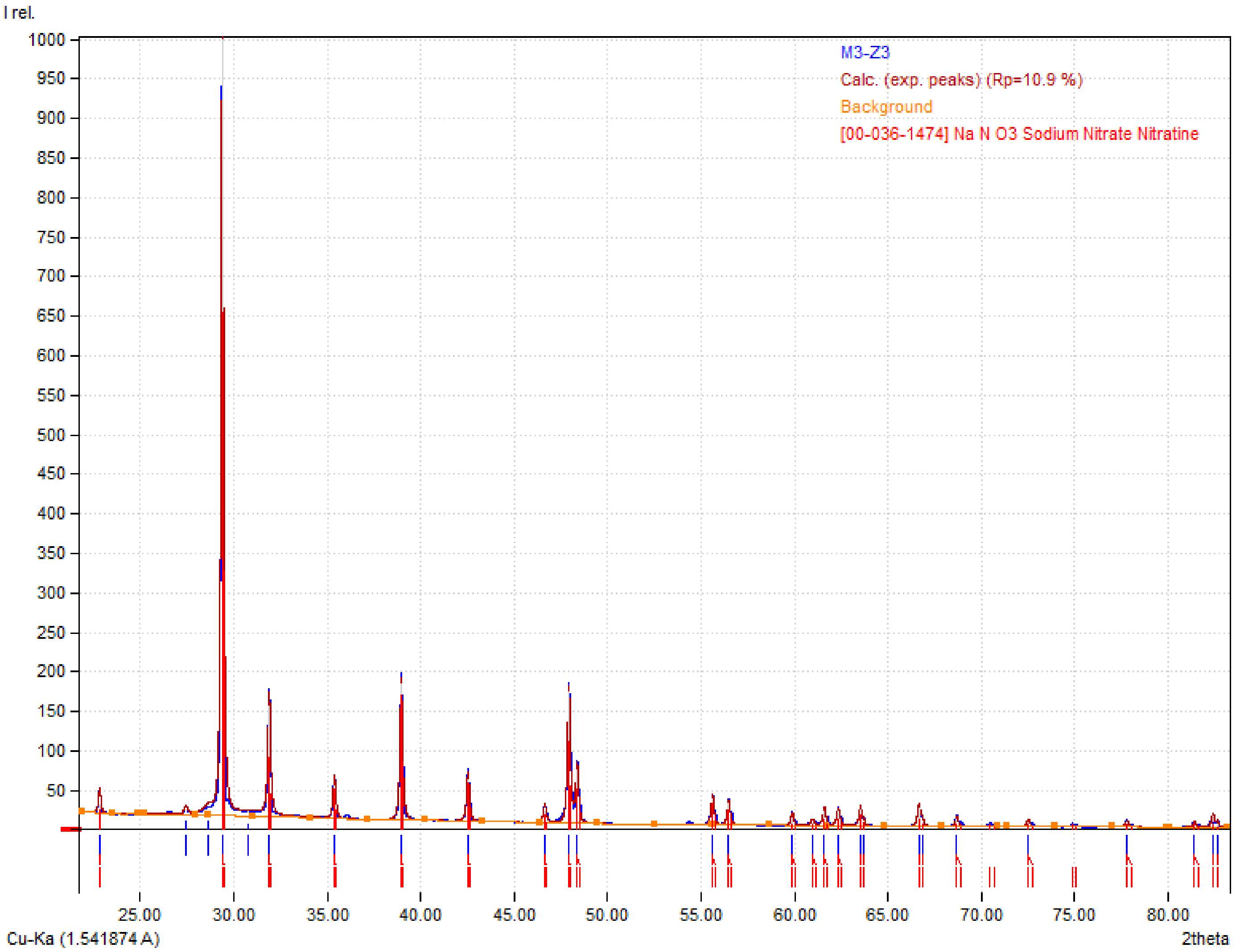
CODE	X	Y	PLACE
HC-01	820730,449	38413,811	La Salle School
HC-02	820754,681	38560,237	La Inmaculada School
HC-03	820768,924	38655,263	Residential house
HC-04	820779,211	38716,932	Imbabura prefecture
HC-05	820780,887	38736,455	Shoppping place
HC-06	820790,507	38795,755	Shoppping place
HC-07	820786,499	38821,684	Residential house
HC-08	820850,213	38871,617	Pedro Moncayo park statue
HC-09	820816,612	38937,500	Episcopal chapel
HC-10	820894,347	38933,993	Catholic Cathedral of Ibarra
HC-11	820787,684	38843,985	GAD Ibarra
HC-12	820807,073	38979,806	Bank
HC-13	820841,925	39081,358	Shoppping place
HC-14	820854,568	39160,923	Residential house
HC-15	820867,171	39228,082	Residential house
HC-16	820871,642	39254,169	Maria A. Hidrobo School
HC-17	820884,010	39393,496	Santo Domingo church
HC-18	820956,921	39282,837	Residential house
HC-19	820947,374	39207,102	Residential house
HC-20	820930,749	39105,844	Shoppping place
HC-21	820920,611	39030,960	Residential house
HC-22	820925,086	38970,225	Phone bussiness (CNT)
HC-23	820706,217	38846,262	Edificio Flores
HC-24	820591,233	38857,802	Shoppping place
HC-25	820568,972	38861,248	Shoppping place
HC-26	820586,542	38898,351	La Merced church
HC-27	820949,263	38897,987	Jusctice Court Ibarra
HC-28	821001,456	38880,484	Bussiness place
HC-29	821022,086	38854,781	San Agustin church
HC-30	820955,647	38789,786	Diocesano Bilingüe School
HC-31	820874,331	38772,883	Former Teodoro G. School
HC-32	820914,216	38705,110	28 de Septiembre School
HC-33	821016,762	38668,520	Abandoned residential house
HC-34	821116,807	38652,780	Residential house
HC-35	821117,347	38672,834	Residential house
HC-36	821227,376	38650,578	Old well-preserved inhab. house
HC-37	821115,529	38569,643	Shoppping place
HC-38	821023,444	38571,596	Residential house
HC-39	820981,969	38590,143	Shoppping place
HC-40	820878,318	38597,382	Shoppping place
HC-41	820863,588	38491,587	Shoppping place



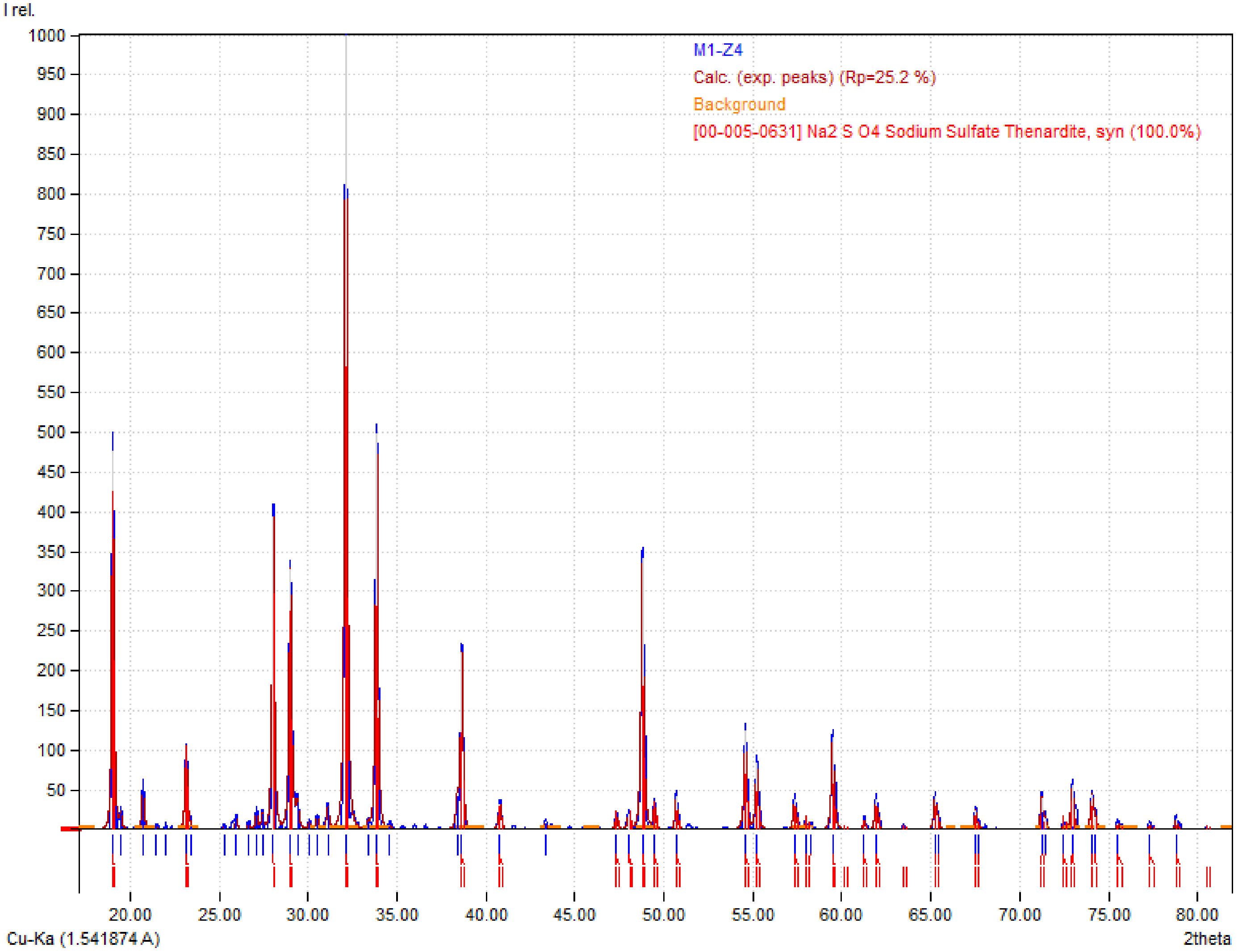
Annex 2. X-ray diffraction pattern of sample M4-Z1



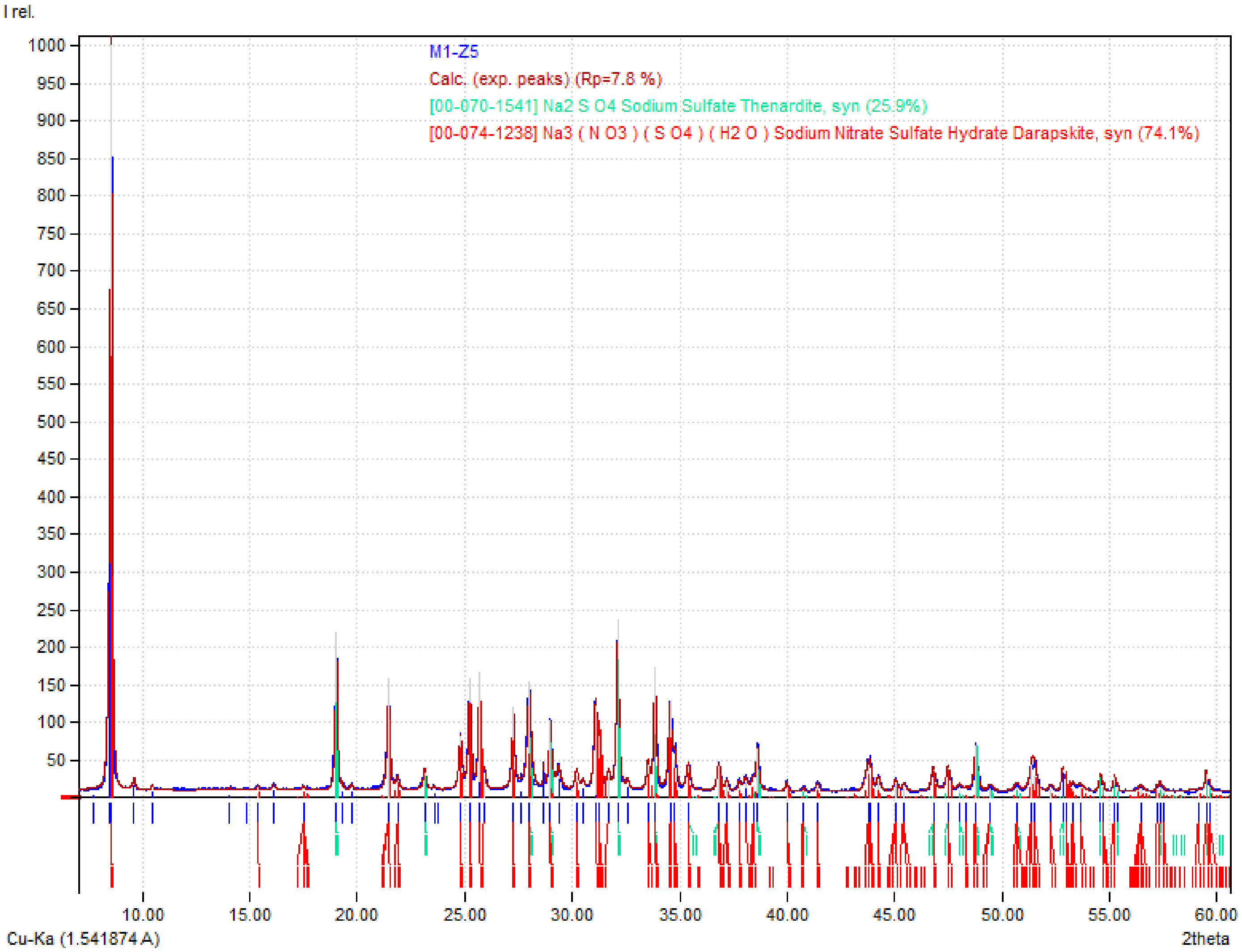
Annex 3. X-ray diffraction pattern of sample M1-Z2



Annex 4. X-ray diffraction pattern of sample M3-Z3



Annex 5. X-ray diffraction pattern of sample M1-Z4



Annex 6. X-ray diffraction pattern of sample M1-Z5