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RISK ASSESSMENT APPLIED TO A MINERAL COLLECTION

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Abstract

In this work, a risk assessment approach was applied to the mineralogical collection at the National Museum of Natural History and Science of the University of Lisbon, Portugal. This collection is in a historical building dated from the 17th century and rebuilt in the 19th century, which had suffered from a major fire (in 1978) that destroyed two-thirds of the mineral collection. There are also other risks affecting this collection and it is not simple to decide which are the most pressing. Consequently, an approach to establishing priorities and planning improvements is imperative. The semi-quantitative Cultural Property Risk Analysis Model was applied to this collection. The magnitude of the specific risks for this mineral collection was calculated to provide a well-informed decision making, taking into account the type of mitigation strategies possible to implement in a historical building. The major hazards affecting this collection were: physical forces, fire, pollutants, light, and incorrect relative humidity. Some of the mitigation actions proposed involved finishing repacking all minerals with padded supports, conduct treatment and encapsulating RH-sensitive specimens in microclimate conditions, improve showcase insulation, reduce illuminance in the exhibition. Although this work was applied to a specific mineral collection, many other natural history museums suffer from similar risks as the ones reported in this work.

***Keywords**: Mineral Collection; Preventive Conservation; Risk Assessment; Mitigation Strategies*

Introduction

Mineral collections are used as scientific research tools, education programs and are associated with historic, scientific, didactic, aesthetical, and economic values. Mineral collections may also be the only way to research material from deposits, mines and sites which are now closed, difficult or impossible to access [1–3]. As cited by Young [2], minerals are "elements in a nation's heritage as important as any work of art, historic building or wildlife site". Currently, the National Museum of Natural History and Science (MUHNAC) has a mineral collection of around 10 756 specimens from various points globally, former Portuguese Colonies, several mines in the country (some closed, some still in operation), private collections, and also offered by similar museums.

MUHNAC has a mineral collection with a selection of high-quality specimens from the main mines in the world, therefore having national and international importance. Some specimens also have artistic value, others have great museography interest and there is a

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historical importance associated with this collection as part it illustrates the history of concepts in mineralogy. This mineral collection is used for museography activity (exhibitions) as well as for scientific research.

The aim of this work was to apply a risk assessment model to MUHNAC's mineral collection in order to define and support the decision-making process. An approach to establishing priorities and planning improvements is imperative in order to help MUHNAC's managers to make informed decisions on allocating the limited resources for the minerals collection preventive conservation [4–6].

Experimental

Materials and Methods

The methodology used in this work comprise: building location and history; building surroundings; mineral collection characterization and condition survey, detailed description of the storage and exhibition rooms, including monitoring of environmental parameters. A risk analysis model was selected, and the information gathered through these procedures was applied to the model. All data regarding mineral collection characterization and condition survey, monitoring of environmental parameters, and risk magnitude calculation was documented using Microsoft® Excel worksheets.

Building location and history

The National Museum of Natural History and Science holds a significant mineral collection, with a total of 10 756 specimens. MUHNAC is located in Lisbon, Portugal (38°43'03.8"N 9°09'03.0"W) inside a historical building. This neoclassical building was constructed for the Polytechnic School of Lisbon, on the rubble of another building destroyed by a fire in 1843. The mineral collection (among other collections) was transfer to this building in 1858 after some renovations. In 1978 another fire occurred, wherein approximately 5,400 mineral specimens (one-third) were saved from a total collection of around 15 000 specimens. The building walls are composed of limestone mortar and after the fire of 1978 they were reinforced with concrete and the floors with cement plate. The Museum building is rectangular with a cloister in the centre and it has four floors.

Building surroundings.

According to climate norms from 1971 to 2000 of Lisbon Geophysics station [7], January was the coldest month with the temperature average of 11.3ºC, while August was the hottest month with an average of 22.9ºC. December was the month with greater precipitation with an average of 121,8mm and July was the month with the least precipitation with an average of 6,1mm [7].

According to the Seismic Susceptibility Map of National Authority for Civil Protection, the Lisbon region is classified as highly susceptible to earthquakes [8, 9]. In Portugal there is a considerable number of recorded earthquakes such as the earthquakes of 1755, 1909 (Benavente) and 1969 (Banco de Gorringe) [8, 10, 11]. The 1755 Lisbon earthquake had its epicentre near Banco de Gorringe (Atlantic Ocean) and had an estimated magnitude of 8.7 in Richter scale [8]. This earthquake is considered to be the most destructive earthquake in Portuguese history and destroyed a great part of Lisbon [12]. As reported by the 2011 IPMA seismic activity summary report [13], 2005 earthquakes with a magnitude between 0.3 and 4.9 were recorded in Portugal.

As stated by the Curator, MUHNAC's building does not have an anti-seismic structure. The 1755 earthquake caused damage to the building, while the 1969 earthquake caused no damage to the building or the collections.

MUHNAC is located in an urban area and the main facade faces southwest towards the traffic road (storage and exhibition are facing southeast, to the Botanic Garden). Currently there is no pollutant monitoring being conducted by the museum. The *QualAr* station (air quality monitoring database created by the Portuguese Environment Agency, APA) used in this study was in *Entrecampos* (approximately 3 km from MUHNAC) [14].

Mineral collection characterization

The mineral collection was characterized by the presence of minerals with special characteristics (light-sensitive, RH-sensitive).

Mineral collection condition survey

The condition survey performed included minerals with incorrect support, fragile minerals, particulate matter accumulation, and minerals with signs of decay. A particular condition survey of pyrite and marcasite was also conducted.

Detailed description of the storage room

The mineral collection is stored in floor -1 inside the "Geology Storage Room 1" and "Geology Storage Room 2". The "Geology Storage Room 1" is the main storage and has approximately 79m^2 (207m^3). The construction of the walls is made of reinforced concrete, while the ceiling has a cement plate and the floor has a double cement plate. This room has a total of 2 wooden doors and several small windows in the upper part of the wall that faces an interior hallway. The storage hallway is 62cm wide. On one side of the hallway, there are cabinets with metal drawers which possesses most of the minerals in storage. There are approximately 10 529 minerals in both storage rooms. Smaller specimens are stored in metal cabinets with metal drawers (10,312 minerals) (Fig. 1 and 2).

Fig. 1. Photo of the Geology Storage Room 1 hallway and metal cabinets

Fig. 2. Example of minerals organization inside drawers

These cabinets are 12cm from the floor. Each drawer contains 1 to 59 minerals, depending on the mineral's size. Some drawers are difficult to open, so it must be done carefully (221 drawers, 27% of all). Most specimens are stored in 40-year-old grey card trays (not acid-free). The trays are joined at the side with staples (no oxidation is visible). Other specimens are stored inside similar brown card trays and white card trays. Different storage materials can be seen within this storage room:

- Open card trays with staples without other support;
- Minerals inside plastic tubes/boxes on card trays;
- Minerals inside glass containers (sealed or not) on card trays;
- Minerals on Styrofoam® polystyrene foam base on card trays;
- Minerals on Stratocell® polyethylene foam base on card trays;
- Minerals inside Minigrip® plastic bags on card trays.

Larger specimens are stored in metal cabinets with shelves inside and outside the "Geology Storage Room 1" (11 cabinets, 176 minerals), and inside "Geology Storage Room 2" (4 cabinets, 41 minerals). These cabinets are 12 and 7cm from the floor, respectively. None of the cabinets are floor/wall fixed. The "Geology Storage Room 1" has a total of four smoke detectors connected to a fire alarm that is transmitted to the museum security. There is a Dry Chemical fire extinguisher (effective on Class A, B and C fires) placed inside the storage and another placed in the hallway outside the storage; and two Carbon Dioxide fire extinguishers (effective on Class B and C fires) placed in the hallway outside the storage.

Detailed description of the exhibition room

Currently, the mineral specimens can be viewed in four different exhibition rooms: "Minerals: identify, classify", "Jewels of Earth: Panasqueira Ore", "Mar Mineral: Science and Natural Resources on the Deep-Sea Floor" (all in floor level 0) and "SPECERE" (floor level 1). A total of 227 minerals (approximately 2,1% of the mineral collection) are on display for public viewing. The *"Minerals: Identify, classify"* exhibition room was selected for this study, since it can be considered the main one, presenting a greater variety of minerals.

This exhibition room has a total area of 225m^2 (1,013m^3). The walls of this room are made of cement, but the construction is unfinished since it does not have insulation. The floor is made of cement with an industrial grey carpet on top. The area has a total of five wooden doors (one facing outside) and seven windows with closed wooden shutters (all facing the Botanical Garden). This exhibition has a total of 170 minerals on display and has been open to the public since 6th December 2001. In this exhibition room, it is possible to see 3 distinct types of showcases (type A, B and C) and 2 types of supports (support F). Table 1 resumes the different types of showcases and respective structure information.

Table 1. Type of exhibition showcases

Showcase-type-A		Showcase-type-C	
	**N° of showcases:** 12 **N° of minerals:** 162 **Materials:** • Metal and glass structure • MDF wrapped in acrylic velvet base and supports • Acrylic supports • Glass shelfs • Interior LED tubes		**N° of Showcases:** 1 **Minerals:** 1 **Materials:** • Metal and glass structure • Interior LED focus

Showcase-type-B		Supports-F	
	 **N° of Showcases:** 4 **N° of Minerals:** 5 **Materials:** • MDF stand • Crystal acrylic case • Outside LED focus	  **N° of Supports:** 2 **N° of Minerals:** 2 **Materials:** • **F1:** Metal structure / **F2:** MDF with pallets • Outside LED focus	

The exhibition room has a total of four smoke detectors connected to a fire alarm that is transmitted to the museum security. There are two Dry Chemical fire extinguishers and one Carbon Dioxide fire extinguisher place inside the room.

Monitoring of environmental conditions

Only the "Geology Storage Room 1" has both temperature (T) and relative humidity (RH) monitoring and control. This storage room has a mechanical ventilation system (*DST Seibu Giken RECUSORB DR-030C*) linked to a wall humidistat (*REGIN HMH 10A, 250 VAC*) to keep RH at 55% and T around 18-20ºC. There is also a portable dehumidifier (*JuneX DJ12*) to help the mechanical ventilation system to keep RH at 55%. To record RH and T there is a thermohygrograph (*RATONA)* and the sheet is reusable and changed annually unless a major change in RH and T occurs. Therefore, to acquire more precise values, two thermohygrometers data loggers (*ROTRONIC HW4-LITE HL-1D / TL-1D*) were placed in the storage room:

- One in the room, near the thermohygrograph;
- One inside a drawer with pyrite specimens.

Regarding light condition, the minerals in the storage room do not suffer damage due to light since they are stored in closed cabinets and the lights are always off unless there is anyone in the room. Therefore, light damage will not be considered in the model as a specific risk inside the storage room. Nevertheless, if light-sensitive minerals go on display, some precautionary measures need to be taken.

The exhibition room does not have a RH and T monitoring or control system. Therefore, six thermohygrometers data loggers were placed in the room:

- Two on opposite sides of the room;
- One inside showcase-type-A of pyrites, since the deterioration of these specimens is caused/accelerated by the presence of oxygen and water;
- One inside showcase-type-A of halite, due to current deliquescence reaction that is now occurring;
- One inside showcase-type-A of autunite and vivianite. Autunite can undergo efflorescence and vivianite is considered as having light-accelerated surface reaction with air, moisture and/or pollutants;
- One inside showcase-type-B of Milky quartz to provide information regarding insulation quality of showcase-type-A and B.

In the exhibition room, damage by ultraviolet and infrared radiation was not considered since the light sources (LED) in the exhibition do not emit these radiations. Illuminance was measured near the minerals in different showcases by using a thermohygrometer, also visible and UV light meter (*764 Environmental Monitor by ELSEC*).

Cultural Risk analysis model selection

In 2019, Ramalhinho and Macedo [15] made a review on cultural heritage risk analysis models. The authors analysed twenty-seven risk assessment models applied to different types of cultural heritage such as immovable property (26%) and movable property (74%). Among those, the authors distinguished several qualitative, semi-quantitative and quantitative models. From those models applied to movable property, it was selected the Cultural Property Risk Analysis Model (CPRAM) which is a semi-quantitative model, developed by the geologist Robert Waller for the Canadian Museum of Nature and applied to mineral, herbarium, and fish collections [5]. Moreover, the CPRAM model has been successfully applied to distinct collections such as paper-based collection kept in an archive [16], artifacts, and specimens pertaining to the Royal British Columbia Museum [17]. In 2013 the American Museum of Natural History also used this model to identify a complete picture of its collections priorities and to do the overall risk assessment of its research, exhibit, and library/archive collections [18]. More recently, the CPRAM model was also applied to an oil painting collection on display, in a historical house [19] and to the storage rooms of Lisbon Museum [20].

The CPRAM is a conceptual, semi-quantitative, and risk-screening model [5]. The result value in this method does not need to be an exact number [15]; it is the relationship between the various magnitudes of risk that is important. The model allows to calculate the Magnitude of Risk (MR) for a period of 100 years and hierarchize the specific risks, providing help in the decision making and management of the collection [15]. The model is founded on the ten agents of deterioration proposed by the Canadian Conservation Institute (CCI): physical forces, fire, water, thieves and vandals, pests, pollutants, light, incorrect temperature, incorrect relative humidity and dissociation [21].

Cultural Property Risk Analysis Model (CPRAM) Application

The magnitude of risk (MR) to collections is calculated by the product of Fraction Susceptible (FS), Loss in Value (LV), Probability (P) and Extent (E): MR = FS x LV x P x E [5]. FS is the most vulnerable fraction of the collection to loss of value. LV is the maximum possible reduction in the utility of the FS. P is the likelihood of an incident may cause damage within a century (100-year period). E is the measure used to indicate which Fraction Susceptible will result in a loss of value over a century [5]. These parameters and MR vary between 0 and 1.

In this study, all parameters are calculated according to the minerals that are currently in storage and exhibition. Some specific risks only happen in the storage room, while others only occur in the exhibition room. The variable Extent is calculated as a function of the Fraction susceptible in order to simplify risk magnitude estimation. When there is no adequate basis to estimate the Extent, the experience of the mineral staff was taken into consideration. LV estimation assumed all minerals are equally important.

Risks can be divided into three types according to their frequency and severity [5]: “Type 1” is considered a rare and catastrophic risk, such as an earthquake. “Type 2” is defined as sporadic and severe, such as incorrect handling. “Type 3”, is a constant and gradual risk, for example, due to incorrect temperature. When the risk is type 1, E value is always maximum (E=1). For risk type 2 and 3, P value is always equal to 1, since the probability of an event to happen in 100 years is certain.

Fig. 3 shows the criteria for the estimation of LV values created and applied to the MUHNAC’s mineral collection, with respective examples.

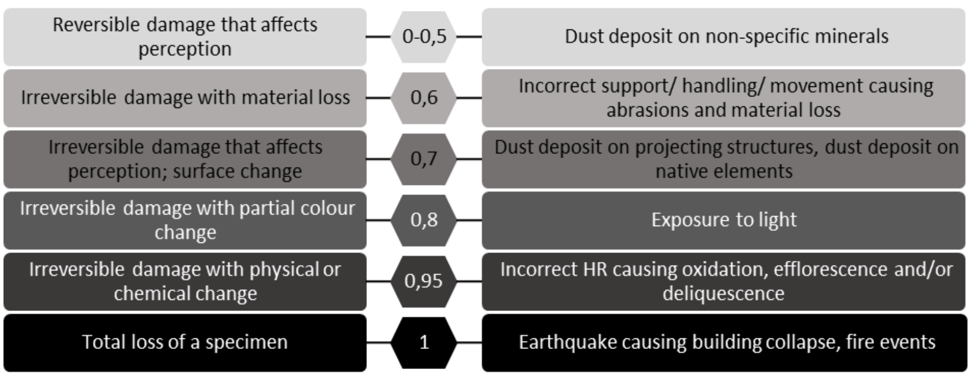

Fig. 3. Criteria for estimation of Loss in Value on the left and examples on the right.

Once the risks associated to the collection are identified and the assessment of the magnitude of each risk has been done, it is possible to hierarchize the risks and propose mitigation strategies.

Results and discussion

Pollutants

The last validated data possible for transfer from *QualAr* website are dated between 01/01/2018 and 31/12/2018 (Table 2). The average and deviation values were calculated with this data from 2018. The estimated values for the storage/exhibition room was calculated according to the dilution rule ("100, 10, 1") proposed by Tétreault [22]. Tétreault [22] and Thomson [23] suggest maximum average concentration limits on particulate matter, ozone (O_3), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) inside museums (Table 2).

Note that most of the collection is located inside cabinets and showcases. Therefore, when comparing the recommended values to those estimated inside cabinet/showcases it is easy to see that the O_3 and NO_2 are higher than the maximum limits proposed by Tétreault [22]. However, NO_2 is within the range proposed by Thomson [23]. Particulate Matter < 2,5μm is another pollutant to consider since it is estimated concentrations are slightly above the limit recommended by Tétreault [22]. SO_2 value is within the limit suggested by literature for the interior of a museum. It is important to notice that these are rough estimations since it does not consider the pollutants produced inside the museum.

Table 2. Average pollutants concentration and standard deviation from 2018 annual data of "Entrecampos" station air monitoring station. Pollutant concentrations inside MUHNAC were estimated according to Tétreault dilution rule [22]

Area \ **Pollutant concentration (μg/m³)**	**Particulate matter <10 μm**	**Particulate matter <2,5 μm**	**Ozone (O_3)**	**Nitrogen dioxide (NO_2)**	**Sulphur dioxide (SO_2)**
***Entrecampos* air quality measurement station**	39,5 ± 14,7	14,0 ± 9,3	30,9 ± 25,7	49,8 ± 26,8	0,8 ± 1,2
Estimation for storage room / exhibition room MUHNAC	3,95 ± 1,47	1,4 ± 0,93	3,09 ± 2,57	4,98 ± 2,68	0,08 ± 0,12
Estimation for inside cabinets / showcases MUHNAC	0,395 ± 0,147	**0,14 ± 0,093**	**0,309 ± 0,257**	**0,498 ± 0,268**	0,008 ± 0,012
Recommended values (100 years) [22]	-	0,1	0,1	0,1	0,1
Recommended values [23]	-	-	0 - 2	≤10	≤10

No detailed information was found in the literature regarding reactions between O_3 and NO_2 with mineral collections. Therefore, the specific risks for these pollutants are not considered in this study. SO_2 can accelerate pyrite decay, acidification of labels/storage media, corrosion of copper and reactions with non-noble metallic minerals, carbonates and borates [22-25]. However, the SO_2 pollutant concentration estimate is within the limit recommended for the interior of a museum. Particulate matter can have an adverse effect on minerals through abrasions of surface, discoloration and impact on visitor's perception [22]. Thus, particulate matter will be the only pollutant considered for risk assessment.

The risk of pollutants by particulate matter will not be considered for the storage room since it has a mechanical ventilation system and the doors are always closed when entering/leaving the room. The metal drawers also prevent the entrance of dust since the top area of the drawers has 1 cm in advance.

Regarding particulate matter in the exhibition room, according to the Curator, showcases-type-B seem to accumulate fewer quantity of dust than type A and C. Supports-F do not have a case, therefore these are always exposed to dust. However, particulate matter was not monitored in this study. Thus, it is only speculated that showcases-type-B accumulate less dust.

Mineral collection characterization

The information regarding special mineral characteristics within MUHNAC's mineral collection was gathered from compilation studies by different authors [26]–[29]. Every mineral name cited in these compilations was searched and counted on the digital database of the mineral collection. Note that the information provided by the authors is not exhaustive [27] (e.g. pink Halite is a light-sensitive mineral and it is not listed by the authors).

Light-sensitive minerals were identified accordingly to Nassau [26] and Horak [28]. Not all colours from a mineral species are light-sensitive (e.g. yellow beryl is not light-sensitive but blue beryl is). For this reason, it was necessary to check the colour of each light-sensitive mineral name. In MUHNAC's mineral collection there are 1 466 light-sensitive minerals. The exhibition room holds 32 minerals currently susceptible to light damage due to the showcase's conditions.

RH-sensitive minerals were identified with Waller's list of mineral specimens that can undergo humidity-related phase transitions [27] and Howie's list of native elements that can suffer problems due to T and RH [29]. Pyrite and marcasite minerals were also counted in this special characteristic. Thus, there are a total of 773 RH-sensitive minerals, of which 202 are named in this study as "non-specific minerals" compiled from Waller's list [27], 304 are native elements and 267 are pyrite/marcasite. Wherein 13 are in the exhibition, from which 5 are non-specific minerals, 6 are native elements and 2 are pyrite/marcasite.

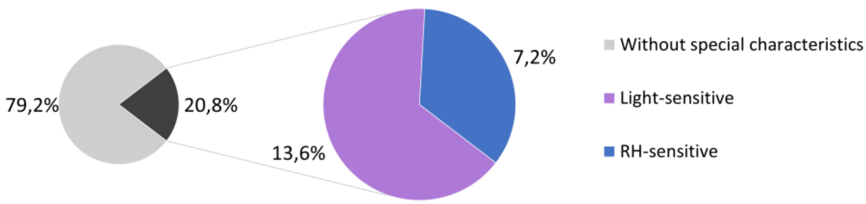

Fig. 4. Percentage of minerals with special characteristics within MUHNAC's mineral collection.

Fig. 4 shows the percentage of minerals without special characteristics, light-sensitive, and RH-sensitive minerals. Most of the minerals in the collection do not have a special characteristic, therefore they are mentioned as "without special characteristics".

Mineral collection condition survey

Storage room

Table 3 represents the condition survey conducted on specimens inside the metal drawers. The survey considered the packaging type, fragile minerals, and specimens under deterioration.

Table 3. Packaging, fragile minerals and minerals under deterioration survey condition conducted in the storage room

Packaging	No padded support.	8 364
	Stored with more than one specimen in the same card tray without partition (overcrowded).	1 636
	Bigger than the card tray.	700
	Large size to be kept inside the drawers, since they can suffer abrasions when opening the drawer. All drawers with minerals in this situation were identified with a white label with black stripes.	37
Fragile minerals	Projecting crystal structures without proper cushioning.	666
Under deterioration (unstable minerals)	Visual signs of decay, such as material loss, chemical reactions. These minerals should be evaluated in detail and preventive measures must be applied. The total also includes pyrite/marcasite's survey.	374

Exhibition room

Table 4 shows the condition survey conducted on exhibition, considering minerals in critical supports, fragile minerals, accumulation of particulate matter, and specimens under deterioration.

Table 4. Packaging, fragile minerals, particulate matter accumulation, and minerals under deterioration survey condition conducted in the exhibition room

Minerals likely to move if there is a strong disturbance/ vibration	Placed in high critical supports inside showcases-type-A.	116
	Inside showcases-type-B[1] susceptible to fall.	2
	Placed in high critical supports inside showcases-type-B.	1
	Inside showcase-type-C susceptible to fall.	1
	On a support-F (F1) susceptible to fall.	1
Fragile minerals if they move/fall	Goethite, Native copper, Rhodochrosite, Aragonite, Dolomite, Gypsum (var. selenite), Torbernite, Fluorapatite, Citrine quartz, Hyaline quartz.	10
	Minerals with projecting crystal structures pointing upwards.	2
	Minerals with projecting crystal structures in the lower area that can develop changes (Stibnite, Halite, Anhydrite, Scolecite over Apophyllite).	4
Particulate matter	Minerals on supports-F accumulate dust more easily because they do not have a case.	2
	Minerals with projecting crystal structures inside showcases-type-A that if left with dust, are difficult to clean without damaging it (Stibnite, Halite, Actinolite, Chrysolite, Scolecite over Apophyllite).	5
	Minerals with projecting crystal structures inside a showcase-type-B that if left with dust, is difficult to clean without damaging it (Anhydrite).	1
Under deterioration (unstable minerals)	Stibnite, Halite, Vivianite, Spodumena (latter is suspected to have changed). These minerals should be evaluated in detail and preventive measures must be applied.	4

[1] Minerals inside some showcases-type-B were not considered since the specimens are heavy, and their showcases height and width dimensions are similar.

Pyrite and marcasite

A condition survey of all pyrite and marcasite in storage and exhibition was carried out (Fig. 7). Fig. 5 shows pyrite in good condition, while Fig. 6 presents a deteriorated pyrite.

Fig. 5. Pyrite in a good condition. MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.7270. Image taken on 23/10/2019

Fig. 6. Pyrite decay. MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.7280. Image taken on 15/02/2019. This mineral is no longer part of the mineral collection

The survey includes visual analysis on shine, presence of powder, cracks, breakage, stained labels, crystal size and shape, and if the specimen consists only of pyrite or if it has another materials present. The condition survey system applied was the following:

- **Good:** no visual problems;
- **Fair**: sign of small cracks, possible dulling, small areas with yellow/white powder;

- **Poor:** several areas affected and with greater severity; specimen is not broken; acidification of labels may occur;
- **Very poor:** specimens completely or very deteriorated; normally show all signs: dull, powder, cracks, breakage, and possible acidification of labels.

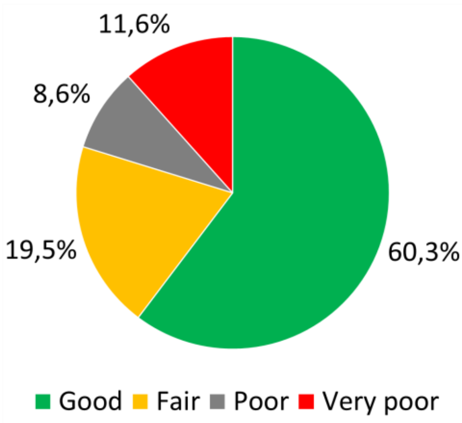

Fig. 7. Condition survey results of pyrite, marcasite, and pyrite with marcasite specimens

Of the 267 minerals, 39,7% (106 specimens) showed some or abundant decay products (Fair + Poor + Very poor). However, some of these visual effects could be related to the 1978 fire, since 71,7% (76/106 specimens) are from collections prior to the fire (these effects were not present immediately after the fire). The two minerals on exhibition appeared to be in a good condition.

Cultural Property Risk Analysis Model (CPRAM) Application

The ten agents of deterioration proposed by CCI were considered for the MUHNAC's mineral collection. The risk magnitude was calculated for physical forces, fire, pollutants, light, and incorrect relative humidity. The remaining agents of deterioration were not calculated since those risks were minimal or non-existent for this mineral collection. The risk magnitude results of the mineral collection are presented in Figure 8.

Physical forces

Physical forces is considered the most common agent of deterioration for minerals [30]. Physical damage can be seen through fissures, cracks, breaks, surface abrasion and material loss (Fig. 9 and 10). Movement (e.g. building vibrations, operating drawers), incorrect handling (e.g. removal/placement of specimens) and incorrect support (e.g. minerals without padded support can jostle against the card tray or other minerals, minerals with projecting structures on the lower area without padded support are more prone to damage due to gravitational forces (Fig. 9 and 10) are some examples of reasons that cause physical damage. Some specimens are more sensitive than others, such as those with projecting crystal structures (e.g. Mesolite, Stibnite) or minerals with a low hardness that can be scratched by a fingernail (e.g. Gypsum).

As it was mentioned, Lisbon is a region classified with high susceptibility to earthquakes [8], [9]. Since there are multiple occurrences of seismic activity in Portugal, two types of risk for earthquakes were considered: type 1 rare and catastrophic, and type 2 sporadic and severe [16]. Type 1 is considered as a strong earthquake with intensity equal or superior to 5 in Richter Magnitude Scale, similar to the 1755 earthquake. This type of earthquake can cause building collapse and/or toppling of cabinets/showcases. While type 2 is considered as a lighter earthquake with intensity < 5, related to smaller earthquakes. This type can cause movement, mixture and/or toppling of specimens.

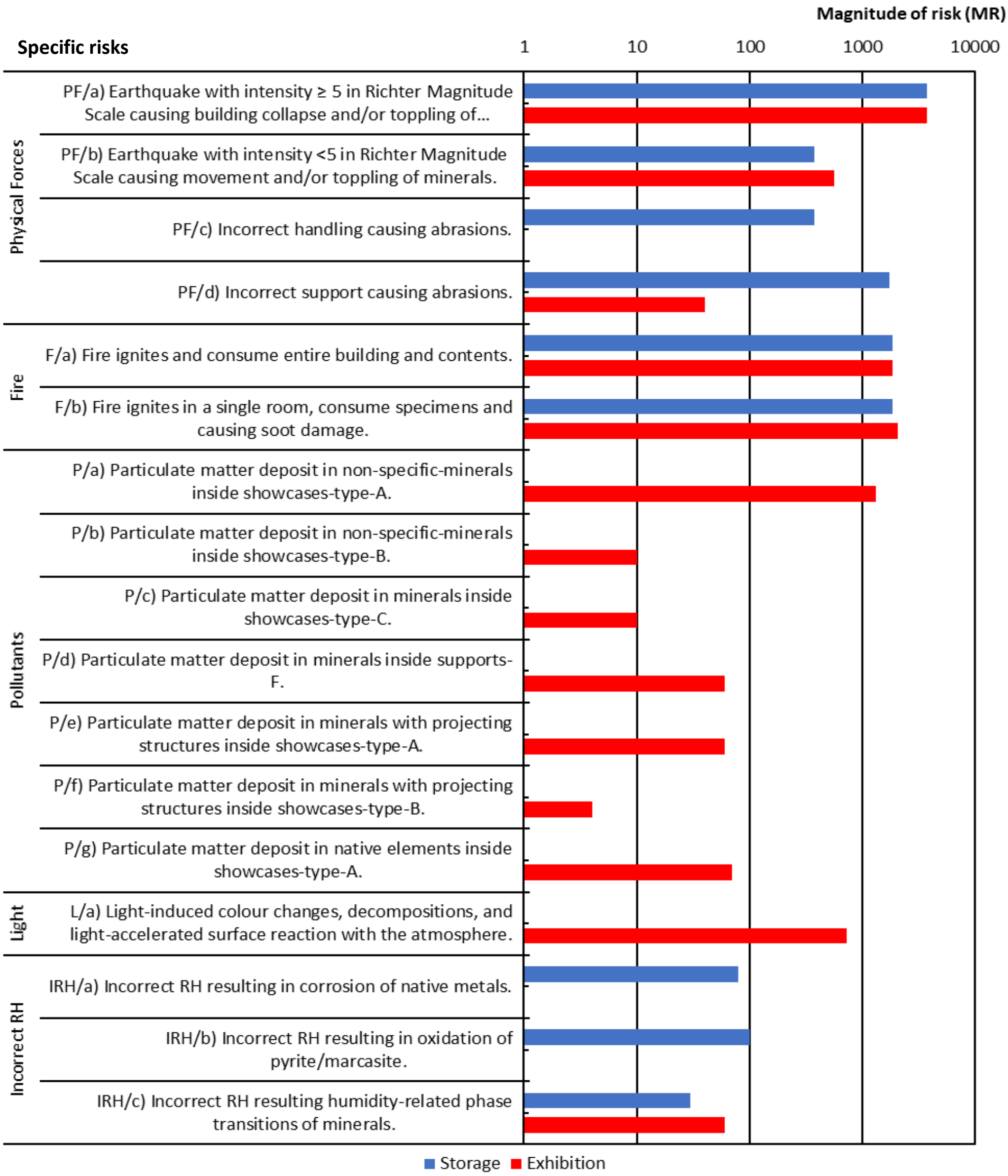

Fig. 8. Risk magnitudes calculated for MUHNAC's mineral collection in storage and exhibition. The MR values were multiplied by 10 000 and a logarithmic scale with base 10 was applied to the axis

Two types of damage were considered for physical forces: small abrasions/partial breakage and whole breakage of specimens. There is no record that the latter occurred due to incorrect handling and support. Therefore, the whole breakage of specimens will only be considered for earthquakes with intensity superior to 5. The general condition survey above contributed to the assessment of the specific risks considered.

Fig. 9. A detail of Mesolite with Styrofoam® base and surface abrasion/material loss on the projecting structures. MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.8847. Image taken on 15/07/2020

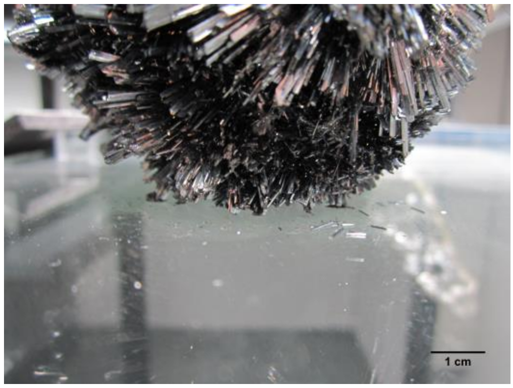

Fig. 10. Detail of Stibnite surface abrasion due to incorrect support/gravitational forces on the projecting structures inside a showcase-type-A. MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.7358. Image taken on 28/08/2020

The estimation of the parameters and MR for the specific risks of earthquakes, incorrect handling, and incorrect support is detailed in As mitigation strategies for the storage room, it was proposed to fix metal cabinets to the floor/walls. A program of repackaging all minerals with padded supports, such as *Stratocell*®, should be continued to reduce abrasion. Minerals that are too large to stay inside drawers should be moved to the cabinets with shelves. Regarding incorrect handling, labels should be clearly visible to reduce the need to handle several minerals to find a specific one. Special care should be taken with drawers that are difficult to open, minerals with projecting structures, and the placement/removal of a mineral from the drawer.

For the exhibition room, individual supports and showcases susceptible to fall could be fixed to the base or floor of the showcases, respectively. Minerals with projecting cristal structures should have padded support in the most sensitive areas. Note that damage due to incorrect handling may also occur during cleaning procedures and exhibition preparation, so special care should also be taken.

Fire

Fire events can be totally devastating by the complete consumption of the building or result in substantial damage by combustion, pollution (soot deposition), high temperature, water (to extinguish the fire), physical forces (crushing specimens due to the activity of the firefighters, the collapse of the building structures) and thieves and vandals (opportunists during the chaos) [31].

Table 5As mitigation strategies for the storage room, it was proposed to fix metal cabinets to the floor/walls. A program of repackaging all minerals with padded supports, such as *Stratocell*®, should be continued to reduce abrasion. Minerals that are too large to stay inside drawers should be moved to the cabinets with shelves. Regarding incorrect handling, labels should be clearly visible to reduce the need to handle several minerals to find a specific one. Special care should be taken with drawers that are difficult to open, minerals with projecting structures, and the placement/removal of a mineral from the drawer.

For the exhibition room, individual supports and showcases susceptible to fall could be fixed to the base or floor of the showcases, respectively. Minerals with projecting cristal structures should have padded support in the most sensitive areas. Note that damage due to incorrect handling may also occur during cleaning procedures and exhibition preparation, so special care should also be taken.

Fire

Fire events can be totally devastating by the complete consumption of the building or result in substantial damage by combustion, pollution (soot deposition), high temperature, water (to extinguish the fire), physical forces (crushing specimens due to the activity of the firefighters, the collapse of the building structures) and thieves and vandals (opportunists during the chaos) [31].

Table 5. Magnitude of Risk calculation for specific risk due to Physical Forces

Specific risk		Type of risk	Risk magnitude calculation					Room
			FS	LV	P	E	MR	
PF/a)	Earthquake with intensity ≥5 in Richter Magnitude Scale causing building collapse and/or toppling of cabinets/showcases.	1	1	1	0,38	1	**0,38**	Storage
								Exhibition
PF/b)	Earthquake with intensity <5 in Richter Magnitude Scale causing movement and/or toppling of minerals.	2	0,794	0,6	1	0,08	**0,038**	Storage
			0,712	0,6	1	0,132	**0,056**	Exhibition
PF/c)	Incorrect handling causing abrasion.	2	1	0,6	1	0,063	**0,038**	Storage
			-	-	-	-	-	Exhibition
PF/d)	Incorrect support causing abrasion.	3	0,794	0,6	1	0,363	**0,173**	Storage
			0,024	0,6	1	0,25	**0,004**	Exhibition

The last violent fire was in 1978 which led to the loss of two-thirds of the mineral collection. The worst effects on the saved minerals were the fragmentation, water damage on labels and the deposit of a dark layer on the surface of the specimens (Fig. 11 and 12).

Fig. 11. An example of a fragmented Quartz affected by smoke and black soot and material loss from the fire. This specimen is no longer part of the collection; serves as an exemplification of the fire damage. Image taken on 13/02/2020.

Fig. 12. An example of Calcite affected by smoke and black soot from the fire. MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.1473. Image taken on 13/02/2020.

A fire of those dimensions is not expected to occur again since new facilities, policies, and fire codes were implemented. Currently, MUHNAC has reinforced concrete walls and cement plates between the floors in the areas where the fire occured, several smoke detectors, a manual fire alarm, various fire extinguishers, 24h security vigilance and several hydrants surrounding the building. The electricity board on the exhibition room is turned off when it is closed to visitors, while in the storage room only the lights breakers in the room are turned off (some equipment needs to keep functioning, such as the dehumidifier). The museum's central system is directly connected to the museum's security booth, where there is a monitor that alerts to the sector in question. After analysing the situation, the Firefighter Station (*Campo de Ourique's* Firefighter Station, approximately 4 minutes from MUHNAC) is then contacted.

The fire risk assessment was followed by Tétreault's study [31], which was also applied by Fernandes [32] and Ramalhinho [33]. Regarding the sets of measures to prevent, detect and respond to a potential active fire within an institution, it is possible to establish a Control Level (CL) for a museum [31]. The CL can be established on a scale of 1 to 6 in which CL1 represents the least efficient protection against fire, while CL6 represents the best protection [31]. MUHNAC is considered a CL1 museum. Thus, the frequency of a fire occurrence for CL1 is estimated to occur every 140 years and the extent of a fire confined to a room is 29% and to the building is 26% [31].

The estimation of the parameters and MR for the specific risks of fire ignites for an entire building consumption and a fire confined to a single room are presented in Table 6.

Table 6. MR calculation for specific risk due to Fire

Specific risk		Type of risk	Magnitude risk calculation					Room
			FS	LV	P	E	MR	
PF/e)	Fire ignites and consume entire building and contents.	1	1	1	0,186	1	**0,186**	Storage Exhibition
PF/f)	Fire ignites in a single room, consume specimens and causing soot damage.	1	1	1	0,207	0,9	**0,186**	Storage
			1	1	0,207	1	**0,207**	Exhibition

Sprinklers systems could be implemented for storage and exhibition. In the storage, wooden windows should be removed, and wooden doors should be replaced by fire doors. This proposal is not recommended for the exhibition room since it would significantly influence the historic aesthetic of the building. It is advisable the periodic verification of the smoke detectors, alarm system, fire extinguishers and electric board.

Pollutants

Particulate matter will impact aesthetical observation, visitor's perception and apparent colour change (Fig. 13 and 14). Minerals which have projecting structures are easily damaged by dust cleaning and most of them are not cleaned (e.g. Stibnite and Actinolite). If particulate matter is allowed to accumulate, it may initiate or accelerate corrosion since the particles can absorb moisture and acids (especially damaging for native elements) [29].

Fig. 13. Quartz amethyst with particulate matter inside Showcase Type C

Fig. 14. Quartz amethyst partially cleaned inside Showcase Type C

The assessment of this risk considered the particulate matter accumulation in different types of specimens, inside distinct showcases. However, there was no adequate basis for estimating of the Extent on particulate matter accumulation on showcases, so the experience of the mineral staff was taken into consideration. The scale on Figuire 15 was proposed for the estimation of the parameter Extent. The parameters and MR estimations for the specific risks of pollutants are presented in Table 7.

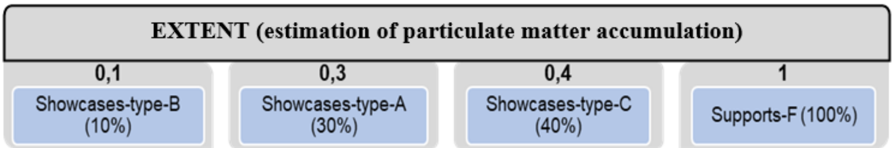

Fig. 15. Proposed scale for Extent estimation

Table 7. MR calculation for specific risk due to Pollutants

Specific risk		Type of risk	Magnitude risk calculation					Room
			FS	LV	P	E	MR	
P/a)	Particulate matter deposit in non-specific-minerals inside showcases-type-A.	3	-	-	-	-		Storage
			0,888	0,5	1	0,3	**0,132**	Exhibition
P/b)	Particulate matter deposit in non-specific-minerals inside showcases-type-B.	3	-	-	-	-		Storage
			0,024	0,5	1	0,1	**0,001**	Exhibition
P/c)	Particulate matter deposit in specimens inside showcase-type-C.	3	-	-	-	-		Storage
			0,006	0,5	1	0,4	**0,001**	Exhibition
P/d)	Particulate matter deposit in specimens inside supports-F.	3	-	-	-	-		Storage
			0,012	0,5	1	1	**0,006**	Exhibition
P/e)	Particulate matter deposit in minerals with projecting structures inside showcases-type-A.	3	-	-	-	-		Storage
			0,029	0,7	1	0,3	**0,006**	Exhibition
P/f)	Particulate matter deposit in minerals with projecting structures inside showcases-type-B.	3	-	-	-	-		Storage
			0,006	0,7	1	0,1	**0,0004**	Exhibition
P/g)	Particulate matter deposit in native elements inside showcase-type-A.	3	-	-	-	-		Storage
			0,035	0,7	1	0,3	**0,007**	Exhibition

In the exhibition, an air filtration system and better insulation of windows and showcases should be implemented to reduce particulate matter accumulation. Minerals with projecting cristal structures inside showcase-type-A are more prone to damage since they cannot be cleaned – these showcases should have priority to decrease particulate matter accumulation. Minerals in supports-F need be regularly monitored and cleaned or moved inside a showcase. Electrostatic dust collectors can be applied to monitored particulate matter deposition.

Light

Many minerals can experience colour changes or be deteriorated by the action of light [34–36]. Light-sensitive minerals can be faded by exposure to light, others become discoloured, and others can be transformed into other compounds [30]. Most of the processes involved in colour alterations are not fully understood and are still under research [26, 36].

Different impurities or imperfections can influence stability (e.g. some brown topaz are stable to light, while others fade rapidly) [26]. However, not all colour changes are permanent, after a period of proper storage (e.g. replaced in the dark) some minerals may restore their original colour [26, 28].

The general illuminance guideline for geological collections is to display specimens at a maximum of 300-350lux [36, 37]. Light-sensitive minerals will quickly suffer colour change if not stored with the appropriate illuminance. These minerals should be store in dark and if on display, should be displayed with a maximum of 50 lux [28, 36].

Fig. 16. Red realgar with partial colour change to yellow. MUHNAC-ULisboa, Colecções de Mineralogia, nº inv: MNHN/UL.6912. Image taken on 13/11/2019

Illuminance monitoring of showcases and light-sensitive minerals on display was conducted. Showcases-type-A and C have high lux values for general mineral collections: values between 354 – 1 644 lux (A9) and 156 – 413 lux (C1), respectively. The supports-F present the lower value of illuminance since the light source is further away: between 69.8 (F1) and 74,4 – 113 lux (F2). The light source in showcases-type-B is placed outside, thus creates a greater distance between the light and the mineral, presenting 90,4 lux (B1). Moreover, the acrylic may eliminate part of the emitted light. Therefore, showcases-type-B present lower values of illuminance than showcases-type-A and C. Nevertheless, all showcases present high values of illuminance for light-sensitive minerals. The highest illuminance value measured was 1 862 lux in a glass shelf of showcase A11 (due to being the mineral position closer to the light lamps).

The light risk assessment considered Nassau’s study on light-sensitive minerals [26]. The author divides these minerals into three groups:

- Light-induced colour changes (LC) without any other physical or chemical changes - may or may not be reversible (e.g. the faded colour of blue Celestite may return to its original colour if stored in the dark): 24 minerals on exhibition;
- Light-induced decompositions producing significant bulk physical or chemical changes (LD) - irreversible effect (e.g. Cinnabar becomes darker with the conversion to black Metacinnnabarite; red Realgar transformation to yellow Pararealgar (Fig. 16)): 2 minerals on exhibition;
- Light-accelerated surface reactions with air, moisture, and/or pollutants (LA) - irreversible effect (e.g. Vivianite darkens on exposure to light and air and it can also disintegrate): 6 minerals on exhibition.

Thus, there are a total of 32 light-sensitive minerals currently on exhibition. Until 2020, 3 minerals suffered colour changes and 1 is suspected to have also changed due to exhibition conditions according to the Curator. In the 1994 “Simpósio de mineralogia” exhibition, one Realgar (Fig. 16) and one pink Halite were displayed in showcases-type-A with an illuminance of fluorescent tubes (no data on illuminance values). Realgar changed red crystals to yellow (decomposition to yellow Pararealgar), while the pink colour on Halite partially faded – both changed in about one to two months. Currently on display, one Vivianite has suffered changes: some of the translucent dark green colour began to darken drastically and also partially fragmented; changes began to occur with the fluorescent lamps. And one Spodumene is suspected to have also changed: the pink colour seems to have faded slightly. The actual exhibition started in 2001, therefore the changes were slow. There is no photograph documentation of these 4 minerals before colour change.

For this generic risk, the three groups described above will be considered in the same specific risk to simplify risk magnitude estimation. The parameters and MR estimations for the specific risks of the three types of light damage are presented in Table 8.

Table 8. MR calculation for specific risk due to Light

Specific risk		Type of risk	Magnitude risk calculation					Room
			FS	**LV**	**P**	**E**	**MR**	
PF/a)	Light-induced colour changes, decompositions, and light-accelerated surface reaction with the atmosphere.	3	-	-	-	-	-	Storage
			0,188	0,8	1	0,481	0,072	Exhibition

Light-sensitive minerals should not be on display. If it is necessary to display, the light lamps could be changed so the lux value will not be superior to 50lux as discussed above. Reducing the intensity of illuminance can minimise the damage, although note that light remains cumulative [28]. Minerals can also be placed further from the light source to lower the illuminance that reaches them or only be visible when a visitor approaches the showcase (e.g. implementation of light sensors or a button to illuminate a light-sensitive mineral). The change of showcases could also be evaluated (showcases with light focus outside the case, such as showcase-type-B may present a good solution). Nevertheless, it is fundamental that all light-sensitive minerals be photographed and documented to evaluate eventual changes and make a decision to prevent further damage.

Incorrect Relative Humidity

Some minerals are susceptible to suffer chemical and physical changes due to the incorrect RH. Hydrates and pyrites can crumble/weep above or below a critical RH level [30]. The most common damages in minerals due to incorrect HR are corrosion/oxidation, efflorescence, and deliquescence reactions.

In this study, pyrite/marcasite, native elements, and non-specific minerals (minerals that undergo humidity-related phase transitions compiled from Waller's study [27]) were considered for this generic risk assessment.

The exact appropriate condition will be specific to the mineral. The recommended values of T and RH for mineral collections, according to the literature, are 16-22 ºC and 50±5% RH [35–39]. Pyrite specimens require a specific RH, the recommended RH is around 30% RH, depending on if the reaction is treated or not [27, 36, 39–45]. Halite can deliquescence at 75% RH [27, 30]. And Borax can dehydrate to Tincalconite at 50% RH - crystals become chalky and friable [27, 30].

Concerning the T and RH monitoring inside the storage room, the values of both thermohygrometers inside the room and drawer are similar and within the recommended limits. The RH inside the room presented an average of 47.6±2.6%, while the pyrite drawer presented an average of 48.0±1.5% (min. 45,7% and max. 52,1%). The values inside the drawer presented lower fluctuations than in the room, as expected. Thus, the results are within the recommended values for mineral collections, however, it is not suitable for minerals that need to be stored in a specific RH, such as Borax and Pyrite.

In the exhibition room, T values measured from all showcases are within the recommended limits, while RH values are higher than the recommended limits and with large fluctuations. Nevertheless, fluctuation decreases slightly inside showcases when compared to the room. The showcase-type-B showed fewer RH fluctuation than showcases-type-A. The RH inside the room presented an average of 64.4±7.6%, while a showcase-type-A presented an average of 66.1±6.8% (min. 46.8% and max. 82.5%), and a showcase-type-B presented an average of 64.3±3.8% (min. 56,1% and max. 73.1%). By comparing the results with the climate normals of the Lisbon Geophysis station, it was found that the room does not have climate control [7]. These results were expected since the room is unfinished, there is no environmental control and it has several windows and a door facing the exterior that does not make the correct insulation. Thus, the room condition is not suitable for mineral collections and for minerals that need to be stored in a specific RH, such Metals, Pyrite and Halite. Currently, only Halite has shown signs of deliquescence that started after changing from fluorescent light to LED. The specimen appeared to be slightly wet and some crystals were loose.

The specific risks will be divided into three chemical deteriorations considering corrosion of native metals, oxidation of pyrite/marcasite, and minerals that undergo humidity-related phase transitions (such as efflorescence and deliquescence). The parameters and MR estimations for these specific risks are presented in Table 9.

Table 9. MR calculation for specific risk due to incorrect RH

Specific risk		Type of risk	Magnitude risk calculation					Room
			FS	LV	P	E	MR	
IRH/a)	Incorrect RH resulting in corrosion of native metals.	3	0,028	0,95	1	0,282	**0,008**	Storage
			-	-	-	-	**-**	Exhibition
IRH/b)	Incorrect RH resulting in oxidation of pyrite/marcasite.	3	0,025	0,95	1	0,4	**0,01**	Storage
			-	-	-	-	**-**	Exhibition
IRH/c)	Incorrect RH resulting humidity-related phase transitions of minerals.	3	0,019	0,95	1	0,142	**0,003**	Storage
			0,029	0,95	1	0,2	**0,006**	Exhibition

As mitigation strategies for the storage room, minerals that can undergo chemical changes should be regularly checked for changes. Pyrite/marcasite in decay can be addressed by conducting treatments and encapsulating specimens in microclimate conditions. Other minerals (native elements and non-specific minerals) currently decaying need to be evaluated and assessed for treatments.

In the exhibition room, new methods need to be applied to help control RH values and fluctuations. Since the room does not have finished construction, the process to keep the room in proper atmospheric conditions becomes difficult. Investment in dehumidifiers or a ventilation system similar to the storage can be expensive and non-sustainable to the museum. Furthermore, the entrance door is always open when the exhibition is open to the public. The long-term proposal is to finish the room infrastructure and purchase a central heating, ventilation and air conditioning (HVAC) system for the entire museum. Some alternatives for quick response are as follows: use of caulking tape for doors/windows to improve the room insulation; control RH inside showcases with microenvironments suitable for general mineral collections. Desiccants, such as pre-condition silica gel or, PRO SORB® in cassettes or sachets are usually used inside museum showcases. Minerals that require a specific RH (such as Pyrite and native metals) are currently stable, but it is recommended that these specimens be regularly monitored for possible changes instead of creating a microclimate suitable for each mineral's stability. Another proposal is the replacement of showcases-type-A for showcases-type-B since the latter showed a better insulation. However, showcase-type-A can be considered to have better museographic display. All RH-sensitive minerals should be regularly monitored for visual changes. Regarding Halite showing signs of deliquescence on exhibition, digital weight measuring should be taken periodically to control more accurately Halite deterioration.

For both rooms, new thermohygrometers should be added to continue to monitor atmospheric conditions.

Conclusions

The application of the CPRAM model to MUHNAC's mineral collection made it possible to identify, characterize and quantify specific risks for this collection. The risk assessment highlighted the most significant risks to establish the priority of mitigation strategies.

The highest risks to this collection are due to an earthquake with intensity ≥5 on Richter Magnitude Scale, and fire events. To mitigate these risks, cabinets/showcases and tall supports should be fixed to the walls/floor, and fire doors (when possible) and sprinklers could be implemented in the museum.

Within the storage room (Fig. 17), the priority should be to continue repackaging minerals with padded supports to reduce abrasion (especially for minerals with projecting crystal structures) (PF/d), PF/b)), conduct a treatment on deteriorated Pyrite/Marcasite specimens (IRH/b)). RH-sensitive minerals that are not currently deteriorating should continue to be regularly checked for changes.

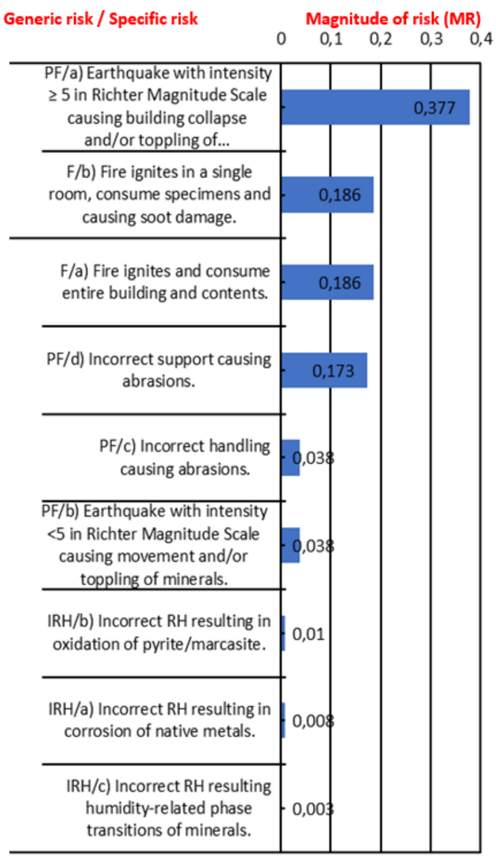

Fig. 17. Risk magnitudes calculated in storage by descending order.

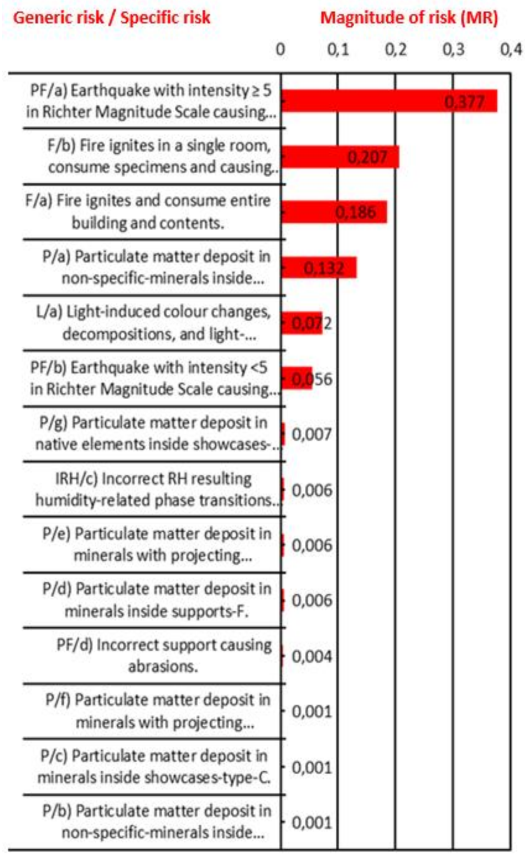

Fig. 18. Risk magnitudes calculated in exhibition by descending order.

The minerals in the exhibition (Fig. 18) presented more specific risks than in storage. Particulate matter deposits in non-specific minerals inside showcases-type-A (P/a)) contribute to more than 80% of the total risks to the mineral collection. This suggests that effort directed at reducing this specific risk will be most significant in reducing overall risks: it can be addressed by investing in an air filtration system and better insulation of showcases to reduce accumulation. The lights should be changed to reduce illuminance or specific display techniques for light-sensitive minerals need to be implemented (L/a)). High critical supports can be fixed to the showcase's base, as well as showcases itself to prevent movement from a possible earthquake with intensity <5 (PF/b)) (center of gravity and the weight distribution must be studied). RH values should be controlled by finishing the room construction, improving the insulation of doors/windows, invest in a dehumidifier, and/or create individual microclimates inside showcases (IRH/c)). RH-sensitive minerals should continue to be regularly checked for possible changes, including native elements and Pyrite/Marcasite minerals, although they are not in decomposition. Showcases-type-B proved to have lower lux values, lessened fluctuations of RH, and are suspected to have less particulate matter accumulation. Replacing showcases-type-A for showcases-type-B may be a good solution as it reduces several risks simultaneously, although showcases-type-A can be considered to have a better museographic display.

The generic risk of thieves and vandals was not considered in both rooms since there are no records of stolen/vandalized minerals in these rooms. However, the security within the storage and exhibition can still be improved by acquiring surveillance cameras and an alarm system with motion detectors when the museum closes. Vandalism can also be reduced by requesting visitors to leave their belongings at the museum entrance, placing limitation barriers for supports-F, and hiring exhibition staff.

This work aims to contribute to the research growth on the care and preservation of mineral collections, help institutions conduct standard methodologies, and thereby promote the preservation of their mineral collections for future generations.

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