

University of Oxford – School of Geography & the Environment

Transfer of Status Report

Assessing the Stability of Mineralogical Collections in Museums

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Abstract

It is widely believed that rocks and minerals are stable objects. Yet approximately 10% of currently known mineral species are vulnerable to conditions found in museums. Inappropriate temperatures, humidity, and light exposure can negatively affect a number of mineral specimens, and produce undesirable changes that result in damage. However, there is a significant lack of scientific research informing the exact conditions and reactions that produce damage in a museum context. This study will respond to this knowledge gap through answering the following questions:

- Which minerals are unstable in museum environments?
- What are the stability parameters for these mineral species?
- How can we best preserve mineral and geological specimens?

This will be accomplished through three main tasks. Firstly, an easy-to-use, openly accessible database will be created as a product of synthesising and analysing research results from a range of fields and disciplines. Secondly, a multiphase collection assessment will be designed and implemented on mineral collections of well-known British museums to verify susceptible mineral species and identify their risk of damage. Lastly, a series of tailored experiments will be designed to confirm the stability parameters of critical mineral species and identify best practice for preservation. Findings from phases two and three will also be added to the database. From these results, the project will provide new data that will inform guidance and standards for the appropriate care and management of mineral collections.

1. Outline of Research Plans

This project is part of the Science and Engineering in Arts, Heritage, and Archaeology Centre for Doctoral Training (SEAHA CDT) funded by the Engineering and Physical Sciences Research Council (EPSRC). It is a collaborative initiative between the University of Oxford, Nation Museum Wales Cardiff (NMC), and BSRIA Ltd., with supervisors from each institution. These are Professor Heather Viles, Dr. Christian Baars, and Ian Wallis, respectively.

Each SEAHA project has partners from academia, heritage, and industry, with each partner providing a supervisor. The project is co-created by these partners to answer specific questions and problems faced by museums and heritage. This particular project stems from a lack of knowledge on the behaviour of geological materials in museum environments. While there is evidence for these materials being unstable, geological collections have not garnered sufficient attention and research to answer the plethora of questions posed by museum professionals. This research project was proposed as a means of rectifying this lack through establishing an awareness of the materials' susceptibility and by beginning the detailed, scientific studies required. This will bring the knowledge up to par with that available for other material types found in museums, such as paintings, ceramics, and archaeological finds.

The scope of the project has been narrowed from geological materials—which encompasses minerals, rocks, fossils, subfossils, and their associated materials—to just minerals, as they are the building blocks of other geological materials. Even still, this is a massive undertaking, as there is a total of 5,575 currently known mineral species (International Mineralogical Association 2020). Yet only a fraction of these are susceptible to deterioration within museum environments. This project aims to fill in current knowledge gaps regarding

mineral stability in a museum context and make this knowledge readily available to the museum sector, by identifying:

- which minerals are vulnerable to museum environments,
- the stability parameters for these mineral species,
- ideal preventative measures to ensure the minerals' longevity.

The following three methods have been identified as means for achieving these objectives.

1.1. Research Synthesis and Analysis of Mineral Stability Data

The aim of this phase is to create a comprehensive database that museum professionals can use as a reference when assessing the conditions required by their collections. Data collated from various fields includes previously identified vulnerable minerals, their stability parameters, and the relevant citations. This is inserted into a database upon analysis alongside additional information, such as the mineral's Hey Index number, chemical formula, and Moh's hardness.

1.2. Collection Assessment

A multiphase assessment procedure has been designed to objectively evaluate the state of mineral collections from well-known British museums to verify susceptible mineral species and identify the risk of damage. This stage is necessary to confirm how well the literature is aligned with reality through identifying overlap, gaps, and variations. Assessments will occur at National Museum Wales Cardiff (NMC), Oxford University Natural History Museum, and others (to be

confirmed). The results from the assessments will contextualise the knowledge available in the database and inform which minerals are examined further.

1.3. Experimentation

A series of experiments will be designed to investigate the deterioration of a select number of vulnerable mineral species, as determined by the findings from the previous two methods. Broadly, the experiments will include methods for hydration, dehydration, light exposure, or pollutant exposure. Various forms of analysis will be used to:

- identify and quantify change,
- determine the stability parameters of chosen minerals to temperature, moisture, light, and pollutants,
- determine the reversibility of these changes.

Macroscopically this plan appears to be a linear flow (Fig. 1), yet it is expected to be iterative, with continual reference and visitation to each phase to a lesser or greater degree throughout the project.

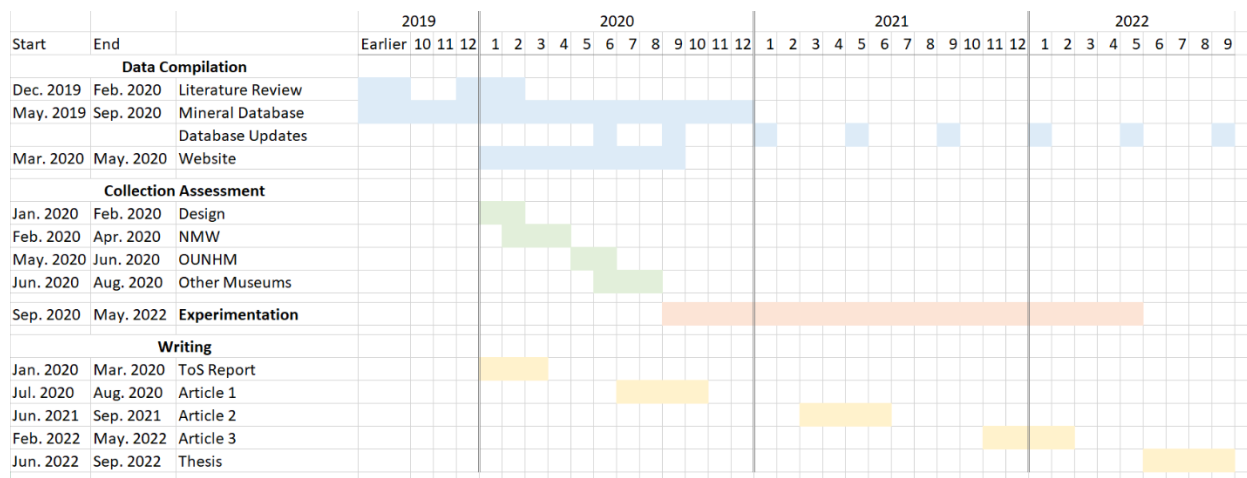


Figure 1. Gantt chart forecasting the research project's timeline to completion.

1.4. Contributions to Field

This research will contribute to improving conservation science. The aim of conservation science is to identify and measure damage—either quantitatively or qualitatively—to provide evidence-based preservation and management strategies. This project will:

- encourage inter- and transdisciplinary research and the use of a range of analytical techniques,
- provide a suggested pathway for determining damage,
- increase the depth and rigour of analyses possible for the field.

It will also make a number of contributions to the museum sector, including:

- bringing current research into the sector from various other fields,
- answering major questions museum professionals have about mineral stability,
- providing information and standards on storage and display conditions as well as a place of accessible reference.

2. Literature Review

What is a Mineral?

A mineral is a homogeneous, naturally occurring solid with a defined and unique chemical composition and crystalline structure. Similarly, a mineral species is “a mineral distinguished from others by its unique chemical and physical properties; it may have varieties” (Mindat.org 2020a), where a variety exhibits a difference in colour, habit, and or minor variations in composition (i.e. amethyst is a variation of quartz).

Minerals are the building blocks of rocks and fossils, and are the raw products for a variety of objects common in daily life (Fig. 2; Emmons 1945). Minerals have been used since prehistory (Whittle 1996, Renfrew 2013) to create pigments, pottery, metals, jewellery, and other objects. As such minerals are ubiquitous throughout museums and heritage sites.



Figure 2. Image taken at the Field Museum (Chicago, IL, USA), displaying various minerals and their resultant products. These include currency, medication, nails, and toothpaste.

Despite the pervasive popular belief that minerals (and other geological materials) are inherently stable—assumed due to their “mineral nature” by Howie (1979a: 103)—at least 10% of currently known mineral species are susceptible to average indoor conditions (Howie 1992a). In fact, this is a long-recorded issue. One of the first documented complaints of mineral deterioration in museums dates to 1922. In his short article, Parsons identified 83 minerals in hopes that by discussing the occurrence of unstable minerals, he could “stimulate a study” (Parsons 1922: 62) of mineral stability parameters. Today, that study continues, and the number of vulnerable minerals is just shy of 500.

There are at least 482 museums with mineral collections across the globe (Mindat.org 2020b). Each museum likely has tens of thousands of minerals in its collections (Kerbey and Horak 2006), of which at least 10% is vulnerable to indoor environments. This means that at least a million specimens are at risk of damage and destruction from inappropriate storage conditions. Many of these million are irreplaceable, due to the values attributed to them.

2.1. Values and Uses of Mineral Collections

Mineral collections have a variety of uses beyond display. These uses are rooted in the values we place upon minerals. Value is the significance humans ascribe to objects. It is a multifaceted, subjective, and often context-sensitive concept (Baars 2010, Robb *et al.* 2013) that varies with the object being assessed, the assessor, and the context. In a museum setting, the values and uses ascribed to objects stem from the information and enjoyment we can extract from them. In addition to their monetary and aesthetic value, mineral collections are valued for their informational and educational potential as well as their historical and cultural significance.

2.1.1. Informational and Research Value

Mineral specimens and their associated materials (i.e. labels, documents) hold information relevant to many fields (Robb *et al.* 2013) that aid our understanding of the world around us. As such, they have a wide range of scientific uses.

Type and figure specimens are incredibly important as they are the original specimens used to define the species (Allmon 1994). As primary sources, they are required to be available for further examination and experimentation to verify a species' properties and characteristics. They are also used to support systematics, such as taxonomy and organisational systems, and can be used to identify complex or unusual specimens brought in by the public (Allmon 1994).

Minerals are evidence of a number of past and present planetary and environmental processes. As documents of the history of life, minerals are used to determine and interpret the past, present, and future (Allmon 1994), and help tackle society's biggest questions and challenges: climate change, resource management, evolution, the origins of life, the potential for extra-terrestrial life, and planetary formation (Putirka 2015, Hazen and Ausubel 2016, The Geological Society 2016).

Mineral collections are also accessible and cost-effective databases for mineral variety and locality (Allmon 1994). It is preferable to use museum specimens rather than going into the field and collecting new specimens. In addition, some sites are inaccessible or no longer exist (Allmon 1994, Baars 2010), so museum specimens are the only evidence from certain localities.

2.1.2. Educational and Outreach Value

Mineral collections are also used as teaching materials for students and the general public (Allmon 1994, Robb *et al.* 2013, The Geological Society 2016). A number of specimens are often set aside by a museum for use as a teaching collection, allowing for visual and tactile learning and engagement. As concrete sources of evidence, these collections are used for teaching about minerals and their properties and to exemplify complex concepts, such as climate change and plate tectonics. They are also used to create an appreciation of science and the natural world (The Geological Society 2016).

2.1.3. Historical and Cultural Value

Minerals, just like any object, can be a link between a material and its people. Specimens can be associated with a particular culture (jades to Chinese culture) or person (Mary Anning's fossils), or have an interesting story and provenance (Robb *et al.* 2013). The specimens carry on the legacies of the people and traditions with which they are associated (Baars 2010, Robb *et al.* 2013, The Geological Society 2016). Many view these legacies as tremendously valuable and powerful, especially when the specimen embodies contextual information. This usually occurs when the specimen is housed in its original case or with original labels (Robb *et al.* 2013). Even better if this associated material is created by the famous person themselves, as with Darwin's microscope slides (Baars 2010).

Mineral specimens can also act as time machines for the history of science. Records and associated material can be informative of what was state-of-the-art and how the specimens were perceived at the time of accession (Baars 2010, The Geological Society 2016).

2.1.4. Potential Value

Values change over time, as does technology, context, and perception. This means that a specimen which has no apparent value now could become valuable in the future (Ashley-Smith 1995, Baars 2010). This is especially true for specimens which have not received rigorous scientific examination. Some specimens have been unknowingly mislabelled or misdescribed, and require reinterpretation based on current scientific understanding and analytical methods (Allmon 1994). Thus, there is the potential for new information and discoveries upon further study.

2.2. Damage: its Causes and Effects

‘Damage’ is a complex and subjective term in museum conservation. This is because it results from changes in both state and value (Fig. 3). ‘Damage’ can be defined as:

the unacceptable degradation of value-defining aspects caused by agents of deterioration.

By the inclusion of the word ‘unacceptable’, one acknowledges that there is a degree of change that can occur before negatively affecting the values and uses of the object (Appelbaum 2007, Robb *et al.* 2013, Strlič *et al.* 2013). It is important to demarcate where this threshold lies in order to define appropriate conditions and suggest when intervention and treatment are necessary (Howie 1979a, Strlič *et al.* 2013). That is why conservation scientists aim to measure damage. Yet this is more complicated than it first seems.

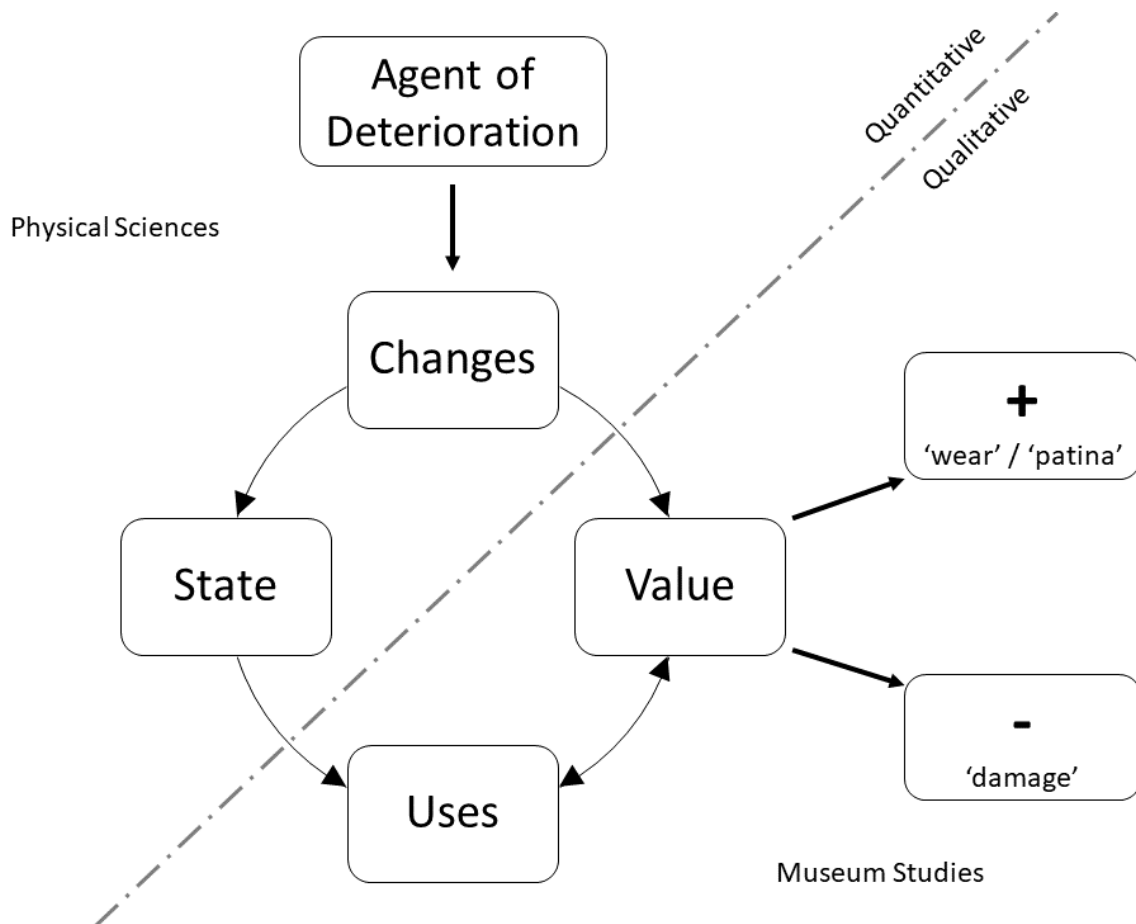


Figure 3. A schematic representation of how an agent of deterioration produces damage (author's own). It is not a straightforward process of cause and effect. Rather, damage is the result of a human's perception that an object's value has decreased through changes in state and or value resulting from exposure to a given agent of deterioration.

Changes to the intrinsic properties of an object are often quantifiable and measurable. The same cannot be said for changes in value, since value is an extremely variable, extrinsic property. The same form of material change often results in varying perceptions of how it affects an object's value depending on the person, material, and context (Ashley-Smith 1995, Strlič *et al.* 2013). This results in different terminology being applied based on the viewer's perception of the change (Ashley-Smith 1995). Take corrosion as an example (Fig. 4). Rusted iron is an exemplary form of *corrosion* and is considered ugly, structurally compromising, and dangerous.

On silver, the *tarnish* is just unsightly, but can be removed by polishing. On copper, the dull brown *tarnish* on coins is tolerable and commonplace, but the green *patina* of sculptures and roofs is often desirable.



Figure 4. Images of three different metals corroding. These are all perceived differently based on the observer and the object's uses and values. 1) The USS Monitor's gun turret made of wrought iron (Newport News, VA, USA). 2) A silver dish with iridescent tarnish. 3) A copper alloy statuette of Isis suckling Horus from the Bristol Museum (UK).

Variations in perception demonstrate that not all change is considered damage, since not all change results in a loss of value (Ashley-Smith 1995, Baars and Horak 2018). And under certain circumstances, some change is desirable or accepted as inevitable (Ashley-Smith 1995, Baars and Horak 2018). This exemplifies the difficulty in objectively measuring damage, and that no singular point of view can be used.

However, it is possible to determine what quantifies as damage by first removing the aspects of value (Strlič *et al.* 2013). This allows for unbiased quantification of how and when material change occurs through the use of analytical methods (Ashley-Smith 1995, Baars and Horak 2018). What material change implies for the object—in terms of its value and use—can be factored back in after material change is appropriately measured (Fig. 5).

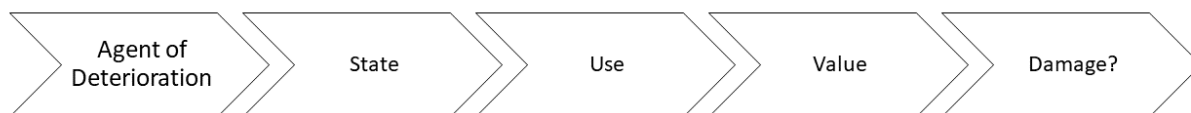


Figure 5. A schematic depicting the suggested means of studying and determining damage (author’s own). One should first begin by studying an agent of deterioration and quantifying the changes in state it produces. One can then determine whether these changes in state result in changes in use and value and if it is ultimately determined to be damage.

By studying change without the influence of value, it is possible to recommend annual limits or doses for each material type to the various agents of deterioration (Table 1). Doses allow for the prioritization and prediction of change (Strlič *et al.* 2013, Baars and Horak 2018). Yet these doses need to accurately reflect the reaction(s) and synergies occurring (Ashley-Smith 1995, Strlič *et al.* 2013). Thus, doses must be expressed as a dose-response function; the magnitude of material change (response) expressed as a function of exposure (dose) over a given period of time. In addition, doses *do* need to be interpreted by values to be of use (Strlič *et al.* 2013), as values define the threshold of when material change becomes unacceptable or when an object no longer has use.

Table 1. The ten agents of deterioration accepted by the museum sector, and examples of them.

Agent of Deterioration	Examples
Temperature	climate, heaters
Moisture	humidity, condensation
Visible Light & UV	sunlight, lamps
Pollutants	carboxylic acids, reduced sulfur gases
Pests	insects, rodents, birds
Physical Forces	poor handling, vibration, collision
Dissociation	loss of or separation from accession information
Fire	gas leaks, faulty electrical components
Water	floods, leaks
Criminals	theft, vandalism

For many agents of deterioration, it is straightforward to determine a dose; exposure should be as low as realistically possible (Erhardt and Mecklenburg 1994). These can be defined by NOAELs (no observable adverse effect level): the maximum amount of exposure that does not produce chemical or physical changes to a given material within specified conditions (Tétreault *et al.* 2003). These levels are based on multiple analytical methods that detect when change is first pronounced, and can be useful measures for determining acceptable doses. Unfortunately, NOAELs cannot be created for temperature and humidity, as their effects are far more complex and nuanced. Thus, one can only mitigate their effects by avoiding extremes and maintaining ideal and stable conditions (Erhardt and Mecklenburg 1994).

As Table 1 shows, collections are at risk from a number of agents. However, many are out of the scope of this project, such as damage caused from fire, water, or criminals. Rather, this project focuses on the agents pervasive to indoor environments and relevant to mineral collections.

How Minerals Change

All minerals have unique stability fields depending on the composition and the ambient pressure and temperature (Hazen and Ausubel 2016). However, some minerals have limited stability fields and form under rare conditions, such as extremely reducing or hypersaline environments. Even slight variations in conditions—be it the presence of other elements, variation in cation ratios, or the pH of the solution—can mean the formation of or alteration to a different mineral species (Hazen and Ausubel 2016).

While only a minority of the currently known 5,575 mineral species are vulnerable to indoor environments, these species are widely represented in collections and are often considered to be rare and difficult to acquire specimens (Howie 1979a, 1984, Hazen and Ausubel 2016). When outside their stability field, these vulnerable minerals will begin to deteriorate into the most energetically stable phase (Fig. 6). The length of time over which deterioration occurs varies from instantaneously to thousands of years (Howie 1984, Hazen and Ausubel 2016).

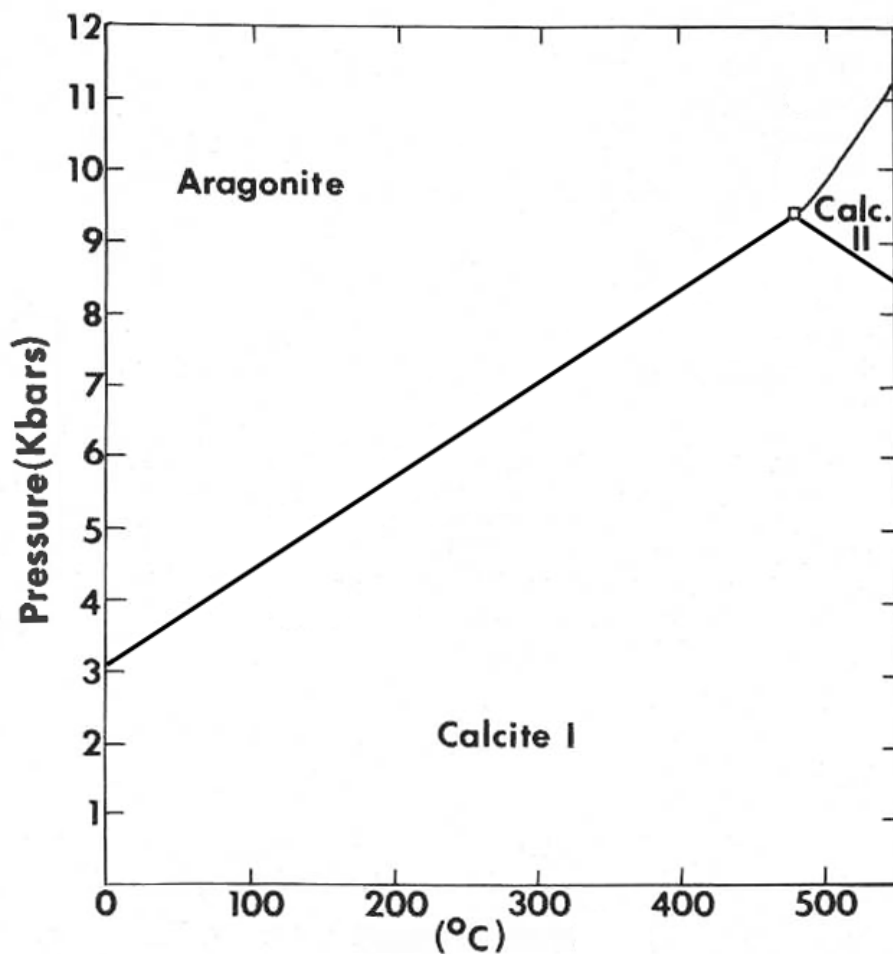


Figure 6. Calcite-aragonite stability diagram, after Crawford and Hoersch (1972). Both calcite and aragonite have the same chemical composition (CaCO_3), but have different crystal structures (trigonal and orthorhombic, respectively). This diagram shows that calcite is stable at lower pressures relative to aragonite. This means that aragonite is metastable at surface conditions. However, the structural arrangement necessary for aragonite to become calcite is sluggish at room temperature, and the process can take thousands of years to occur.

About 500 minerals are susceptible to the temperatures, relative humidity (RH), light, and pollutants common within museum environments (Table 2), whereas all mineral specimens can be damaged by shock, vibrations (Howie 1979a), and abrasion (Kerbey and Horak 2006). By knowing reaction pathways and products, one can implement successful measures to prevent, mitigate, and treat deterioration.

Table 2. A list of chemical reactions that can occur to minerals in a museum environment.

Chemical Reaction	Caused by	Definition of Reaction
Corrosion	Relative Humidity, Pollutants, Light	The (electro-)chemical oxidation of metallic compounds within a mineral.
Dehydration	Relative Humidity	The loss of a mineral's structural or interstitial water.
Deliquescence	Relative Humidity	The dissolution of a mineral through the absorption of atmospheric moisture.
Efflorescence	Relative Humidity, Pollutants	The crystallisation of soluble salts at a mineral's surface.
Hydration	Relative Humidity	The addition of water molecules to a mineral.
Hydrolysis	Relative Humidity	A reaction between a mineral and water vapour that produces new compounds.
Oxidation	Relative Humidity, Light	A change in the oxidation states of elements within a mineral, resulting in new compounds or mineral species.
Volatilization	Temperature	The loss of a chemical substance, other than water, through conversion to a vapour.
Water Film Formation	Relative Humidity	The condensation of atmospheric water on a mineral's surface.

2.2.1. Temperature

There are a handful of minerals that are affected by temperature, regardless of a change in or maintenance of RH. These are usually minerals that contain fluid inclusions or structural water (Howie 1984, Waller 1992). Rapid changes in temperature can lead to fracture (Child 1994, Stanley 2004). Differential temperatures between a specimen's interior and exterior (or between a fluid inclusion and the surrounding mineral) result in increasing stresses, which are then released through cracking or spalling (Waller 1992, Horak 1994). Native sulfur is a well-known example (Howie

1984, Nassau 1992, Waller 1992) that shatters with handling and localised heating from lighting. Waller (1992) lists characteristics that increase the likelihood of a mineral to fracture, including easy cleavage and high brittleness. Heat also generally increases the rate of reactions by providing additional energy for an occurring reaction or sufficient amounts to initiate one (Nassau 1992).

2.2.2. Moisture and Relative Humidity

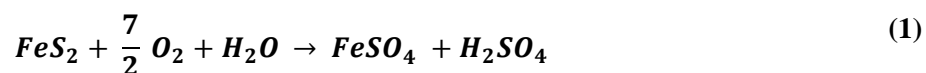
The effects of inappropriate levels or fluctuations in relative humidity are varied and complex, as they are dependent on material type (Erhardt and Mecklenburg 1994). Relative humidity is involved in numerous reactions (Table 2) including phase changes (i.e. hydration, deliquescence, efflorescence) and oxidation (i.e. corrosion). As a result, approximately 330 minerals are susceptible to relative humidity (Waller 1992), and each have different stability ranges which often do not overlap (Erhardt and Mecklenburg 1994, Chou *et al.* 2013).

Hygroscopic material responds to RH fluctuations by absorbing or desorbing moisture (Howie 1979a) to maintain equilibrium with the environment. Yet this process is not instantaneous and may induce stresses throughout the specimen with large RH fluctuations (Erhardt and Mecklenburg 1994). These stresses may result in dimensional changes, cracking, and delamination (Howie 1984, Erhardt and Mecklenburg 1994). Changes in hydration states are also frequent, leading to an altered composition. Dehydration is particularly damaging; the loss of structural water can lead to shrinkage, fractures, and even disintegration (Howie 1984, Waller 1992).

Water-soluble minerals will also absorb moisture from the atmosphere and deliquesce. If deliquescent conditions are temporary, the specimen can slump, round, or flatten when in a semi-liquid phase (Waller 1992). Halite (NaCl) is a prime example, entering solution at 76%RH (Erhardt

& Mecklenburg 1994). Deliquescent minerals can also be affected by hydrolysis or oxidation when in solution (Waller 1992). If present as salts in a porous material, these minerals can migrate through the object when above its deliquescence point. This process occurs with cycles of fluctuating humidity, where the salts enter solution when the RH is above the deliquescence point and recrystallise when the RH drops below it (Howie 1979b, Erhardt and Mecklenburg 1994). Crystallisation at the surface is termed efflorescence and often results in surface disfiguration (Howie 1979b). Recrystallisation can also occur within the material matrix, causing mechanical stress and damage. The presence of soluble salts also increases corrosion potential and susceptibility to pollutants (Erhardt and Mecklenburg 1994).

In geological collections, pyrite decay is the most documented oxidation reaction to occur (Howie 1992b, Blount 1993, Rouchon *et al.* 2012, Odin *et al.* 2014, 2018, Miles 2019), due to the ubiquitous nature of the mineral. Pyrite deterioration is a complex set of reactions; its pathways varying depending on moisture availability. In atmospheric conditions, the reaction is largely chemical, but may be electrochemical with the presence of additional metallic ions (Howie 1979a, 1992b, Rimstidt and Vaughan 2003). In both instances, the initial reaction is the oxidation of sulfur from S²⁻ to S⁶⁺ (Rimstidt and Vaughan 2003) in the presence of oxygen and moisture. Sufficient atmospheric moisture is present at 30%RH to initiate the reaction. As the RH increases, so does the reaction rate (Howie 1979a, Newman 1998, Jerz and Rimstidt 2004), with a marked acceleration at 60%RH (Howie 1992b). The reaction products are ferrous sulfate and sulfuric acid (Eq. 1).



The composition and hydration state of the ferrous sulfate varies with the ambient RH and composition of the specimen undergoing oxidation (Jerz and Rimstidt 2004). These sulfates are

much larger than the initial pyrite (Howie 1992b, Jerz and Rimstidt 2004), resulting in volumetric expansion. If formed within a specimen, the expansion produces intense stresses that often result in the specimen cracking, spalling (Fig. 7), and eventually disintegrating (Wiese *et al.* 1987, Howie 1992b, Blount 1993, Newman 1998, Larkin 2001, Jerz and Rimstidt 2004, Miles 2019).

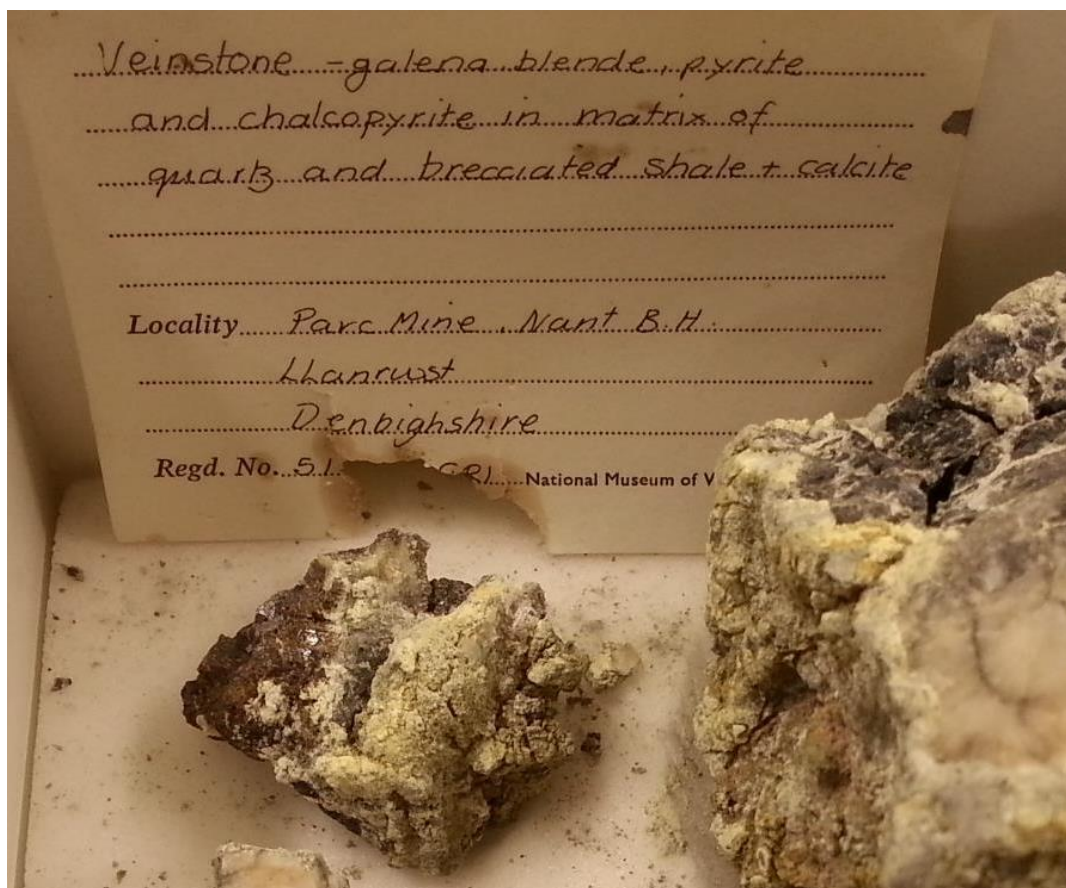


Figure 7. Image of a veinstone specimen affected by pyrite decay. A section has spalled off the body; both feature characteristic yellow & white sulfate efflorescence. Also note the ‘scorching’ of the label, caused by sulfuric acid, which has defaced the accession number. (National Museum Cardiff)

Both sulfuric acid and ferrous sulfate are hygroscopic and often react further with atmospheric moisture (Howie 1992b, Newman 1998, Jerz and Rimstidt 2004). Sulfuric acid may scorch labels (Fig. 7) and housing materials (Howie 1992b, Newman 1998, Larkin 2001, Miles 2019). It may also volatilise and undergo additional atmospheric reactions to produce reduced sulfur gases (Waller *et al.*

2000). These gases, as well as sulfuric acid, are able to dissolve or alter other mineral species (Howie 1992b, Jerz and Rimstidt 2004). Ferrous sulfate frequently undergoes an additional series of reactions. It may hydrate, dehydrate, hydrolyse, or oxidise depending on the ambient conditions. These reactions produce ferroso-ferric sulfates, basic sulfate-hydrates, and ferric sulfates (Howie 1979a, 1992b, Blount 1993, Jambor *et al.* 2000, Jerz and Rimstidt 2004). These sulfates can also undergo further reactions, resulting in a complex series of products.

2.2.3. Light

Light absorbed by specimens can cause colour change or loss, and can activate or accelerate reactions with other decay agents (Nassau 1992, Child 1994). A minority of photosensitive minerals *only* undergo colour change (Howie 1984). A limited number of these display reversible colour change upon removal of the light source or through irradiation (Howie 1984, Nassau 1992, Horak 1994), as these minerals have not been altered physically or chemically. However, light more commonly induces chemical reactions—such as oxidation (Howie 1984) and elemental liberation (Howie 1992c, Nassau 1992)—that can result in the formation of a different mineral species and irreversible colour change. Photosensitivity can be inherent to the mineral or occur through impurities which often act as colourants. The degree of photosensitivity can also vary with the specimen's origin (Nassau 1992), formation conditions, and associated mineralogy.

This is the case with cinnabar (α -HgS). Long used as a pigment in paintings and frescoes (Gettens *et al.* 1972, Saunders and Kirby 2004, Keune and Boon 2005, Radepont *et al.* 2011, Neiman *et al.* 2015), cinnabar from certain localities has been shown to be photosensitive (Dreyer 1938, McCormack 2000), irreversibly blackening with exposure to light (Fig. 8). Photosensitive cinnabar from these localities are associated with a number of mercury halide minerals (Dreyer

1938, McCormack 2000, Neiman *et al.* 2015) and have been determined to contain trace amounts (~1 wt%) of alkali halogens, usually chlorides (Dreyer 1938, McCormack 2000, Keune and Boon 2005). At these concentrations, halogens are integral catalysts in the photochemical redox reaction that produces the darkening (Keune and Boon 2005, Anaf *et al.* 2013, Neiman *et al.* 2015). Moisture also plays a key role in the reaction (Saunders and Kirby 2004, Neiman *et al.* 2015); increasing RH results in a greater colour change from red to black. Although the exact reaction pathway has not been confirmed—due to some confusion of the order of intermediary products—the surficial blackening of cinnabar is attributed to nanoparticles of colloidal metallic mercury (Dreyer 1938, Keune and Boon 2005, Anaf *et al.* 2013, Da Pieve *et al.* 2013, Neiman *et al.* 2015), rather than the long assumed metacinnabar (Gettens *et al.* 1972), calomel, or corderite (Da Pieve *et al.* 2013, Neiman *et al.* 2015).

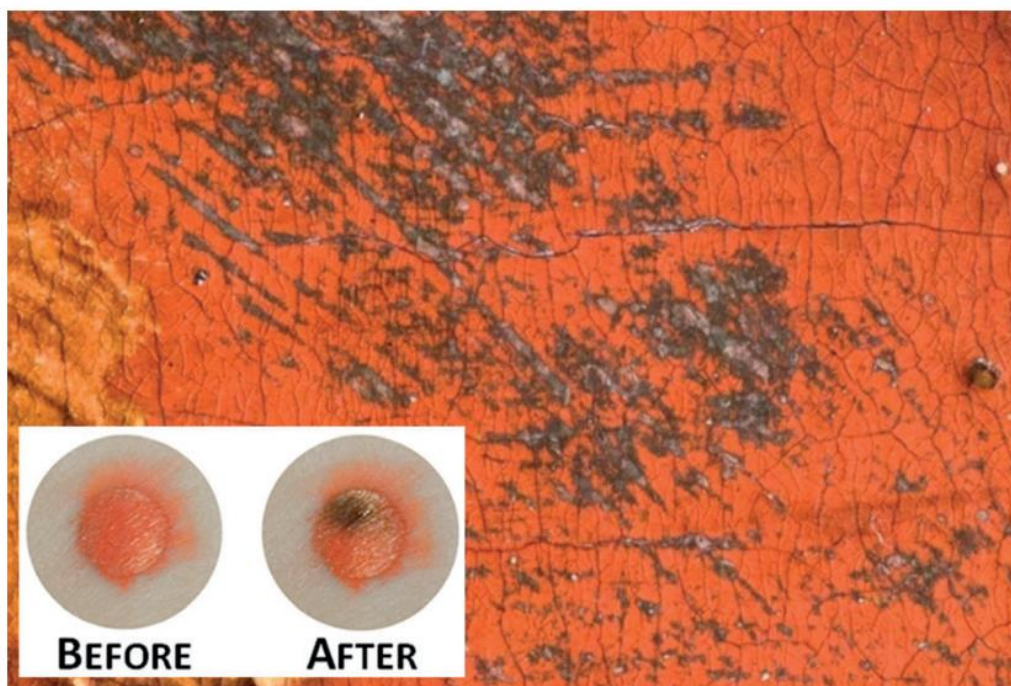


Figure 8. An example of cinnabar's alteration from red to black on Ruben's painting 'The Adoration of the Magi' (from Anaf et al. 2013). The inset shows Anaf's experimental samples of cinnabar before and after light and chloride exposure. In both instances, the black reaction product was identified as metallic mercury.

2.2.4. Pollutants

Museum pollutants are unwanted gases or particulates that cause or accelerate deterioration, with the most frequently mentioned being sulfur gases and carboxylic acids. Internal sources of these include human activity, display and storage materials, and sometimes the objects themselves (Waller *et al.* 2000, Eggert *et al.* 2004, Stanley 2004, Grzywacz 2006). Minerals can release sulfur, silver, copper, mercury, and other volatiles as decay products (Howie 1992a; Waller *et al.* 2000). These volatiles can be absorbed by housing material or be deposited on and react with nearby mineral surfaces, resulting in a compositional change (Waller *et al.* 2000).

Sulfur-containing minerals release sulfuric acid upon oxidation (i.e. pyrite). Other significant sulfur gases include hydrogen sulfide (Howie 1979b), carbonyl sulfide, elemental sulfur, and sulfur dioxide (Waller *et al.* 2000, Eggert *et al.* 2004). These reduced sulfur gases can be emitted from specimens or housing materials (Waller *et al.* 2000, Eggert *et al.* 2004, Lussier and Smith 2007), and damage neighbouring minerals and materials. For example, these gases produce efflorescent copper sulfides and sulfates on copper-containing materials and cause pitting to the substrate (Eggert *et al.* 2004). The formation and composition of the efflorescence is dependent on the ambient temperature, relative humidity, and pollutant type and concentration. Reduced sulfur gases also tarnish metallic minerals, such as those containing silver (Waller *et al.* 2000).

Carboxylic acids (formic acid, acetic acid, formaldehyde, and acetaldehyde) generally originate from wooden housing materials, adhesives, sealants, varnishes, and plastics (Waller *et al.* 2000, Grzywacz 2006, Caracanhas Cavallari *et al.* 2014). These acids corrode metals, especially lead (Tetreault *et al.* 1998, Raychaudhuri and Brimblecombe 2000, Waller *et al.* 2000, T etreault *et al.* 2003). This reaction accelerates with increasing acid concentration, RH (Tetreault *et al.* 1998,

Tétreault *et al.* 2003), and exposure to daylight (Raychaudhuri and Brimblecombe 2000).

Carboxylic acids also dull the surfaces of some borate minerals (Waller *et al.* 2000).

Carbonatic and calcareous material are particularly sensitive to carboxylic acids, which produce a disfiguring white or grey efflorescence (Tennent and Baird 1985, Caracanhas Cavallari *et al.* 2014). This efflorescence (Fig. 9) has been determined to be calcium acetate (Eq. 2), calcium formate (Eq. 3), and or a calcium acetate-formate double salt (Tennent and Baird 1985, Usher *et al.* 2007, Prince *et al.* 2008), depending on the quantity of acetic and formic acid in the environment. Calcium is incorporated from the surface (Usher *et al.* 2007), causing disfigurement of surface features and pitting (Howie 1979a, Caracanhas Cavallari *et al.* 2014). Fractures (Fig. 9) may be produced if salt crystallisation occurs within the specimen.

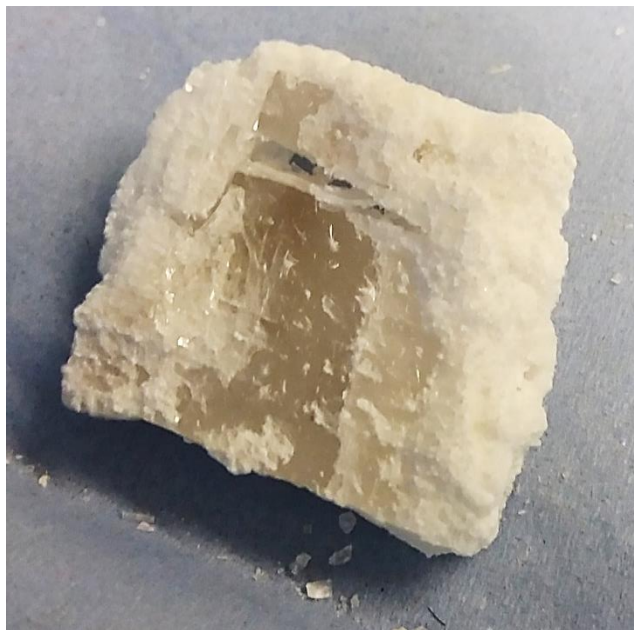
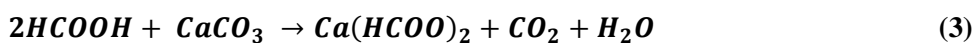
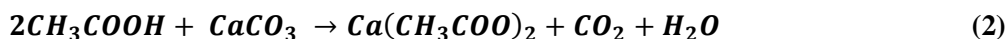


Figure 9. An example of severe calcium acetate efflorescence on calcite, exhibiting a fracture along a growth plane.

The reaction rate increases with increasing RH (Usher *et al.* 2007, Prince *et al.* 2008, Caracanhas Cavallari *et al.* 2014). Water film formation on the calcite surface occurs above 55%RH and gains bulk-like properties at 90%RH (Usher *et al.* 2007). This water film allows for greater mobility and concentration of reactive ions and continually exposes a fresh calcite surface for reaction. The reaction is also enhanced by the presence of hygroscopic salts such as chlorides (Howie 1979a, Tennent and Baird 1985, Caracanhas Cavallari *et al.* 2014).

2.2.5. Methods for Measuring Change

In order to monitor the changes listed above (Table 2), one must be able to measure them. The means of measurement need to be quantitative to allow for tracking and comparing changes over time and across collections. Various analytical techniques (Table 3) have been employed in examining mineral degradation. The methods used are largely spectroscopic, allowing for identification of elements, compounds, and structures. One can determine reaction processes from this data by the comparison of fresh and degraded samples.

Table 3. A selected list of analytical techniques frequently used in the identification of minerals, their changes, and reaction products. This list is not exhaustive, as there are a number of other techniques cited in the literature, albeit less frequently.

Method (Abbreviation)	Identifies	References
Weight	Weight gain or loss	(Tennent and Baird 1985, Tétreault <i>et al.</i> 2003, Baars and Horak 2018)
Colorimetry	Colour change	(Tétreault <i>et al.</i> 2003, Saunders and Kirby 2004, Neiman <i>et al.</i> 2015, Baars and Horak 2018)
Infrared Spectroscopy (IR)	Compounds via bond type	(Tennent and Baird 1985, Putnis 1992, Saunders and Kirby 2004, Al-Hosney <i>et al.</i> 2005, Prince <i>et al.</i> 2008, Rouchon <i>et al.</i> 2012, Odin <i>et al.</i> 2015)
Raman Spectroscopy	Compounds via bond type	(Putnis 1992, Rouchon <i>et al.</i> 2012, Odin <i>et al.</i> 2014, 2019, Neiman <i>et al.</i> 2015)
X-ray Diffraction (XRD)	Compounds via crystal structure (d-spacing)	(Dickson and Tunell 1959, Tennent and Baird 1985, Wiese <i>et al.</i> 1987, Putnis 1992, Blount 1993, Tétreault <i>et al.</i> 2003, Eggert <i>et al.</i> 2004, Usher <i>et al.</i> 2007, Monico <i>et al.</i> 2011, Rouchon <i>et al.</i> 2012, Anaf <i>et al.</i> 2013, Da Pieve <i>et al.</i> 2013, Odin <i>et al.</i> 2014, 2019, Neiman <i>et al.</i> 2015)
Micro-Computed Tomography (μ CT)	Topography & morphology Relative density Inclusions & defects Pore & void space	(Miller <i>et al.</i> 1990, Kyle and Ketcham 2015, Guntoro <i>et al.</i> 2019)
Scanning Electron Microscopy (SEM)	Topography	(Tennent and Baird 1985, Wiese <i>et al.</i> 1987, Putnis 1992, Tétreault <i>et al.</i> 2003, Eggert <i>et al.</i> 2004, Jerz and Rimstidt 2004, Keune and Boon 2005, Rouchon <i>et al.</i> 2012, Odin <i>et al.</i> 2014, 2019, Neiman <i>et al.</i> 2015)
Energy Dispersive X-ray Spectroscopy (EDS or EDX)	Elements	(Tennent and Baird 1985, Putnis 1992, Eggert <i>et al.</i> 2004, Jerz and Rimstidt 2004, Saunders and Kirby 2004, Keune and Boon 2005, Rouchon <i>et al.</i> 2012, Odin <i>et al.</i> 2014, Neiman <i>et al.</i> 2015)
X-ray Absorption Near-Edge Structure (XANES)	Elements Oxidation state Coordination Environment	(Putnis 1992, Radepont <i>et al.</i> 2011, Anaf <i>et al.</i> 2013, Odin <i>et al.</i> 2014, 2015, 2019, Neiman <i>et al.</i> 2015)
X-ray Photoelectron Spectroscopy (XPS)	Elements Oxidation & electronic state	(Putnis 1992, Nesbitt 1998, Tétreault <i>et al.</i> 2003, Usher <i>et al.</i> 2007)

2.3. Knowledge Gaps and Issues to Address

Most minerals which are vulnerable to museum environments have not been sufficiently studied. Pyrite, cinnabar, and calcite are the exceptions. While there are specific questions yet to be answered for these minerals' reactions, the current information present across disciplines is sufficient for museum applications. We know the general reaction pathways and products, from which we can determine ways to prevent, mitigate, and treat their deterioration. Yet the same cannot be said for the vast majority of vulnerable species. This is due to a lack of accessible research and knowledge transference.

Lack of Research

It has been repeatedly said over the past century (Parsons 1922, Howie 1979a, 1992a, Newman 1998, Baars and Horak 2018) that the literature available on mineral stability within the museum sector is lacking. Yet old knowledge continues to be recycled, citing the same articles from 40 years ago. These texts are also generally vague and at times contradictory, especially when defining stability limits. Unfortunately, little new research on mineral stability is being produced by the museum sector. The focus still lies quite heavily on paintings, metals, stone, and archaeology. While some of this information can be extrapolated to mineral and geological specimens, it leaves a gross number of minerals unstudied. In addition, several professionals find that there just simply is not enough time to perform research alongside other museum duties. Novel research often falls by the wayside.

As such, most knowledge on mineral stability comes from other fields (i.e. earth sciences, chemistry, and material science) where it is actively being studied. Yet not all of the literature is relevant for museum collections. Much of the research focuses on how minerals

interact and effect planetary processes in the mantle or upper atmosphere (Rubasinghege and Grassian 2013, Putirka 2015). There is literature of minerals in crustal or mine environments (Jambor *et al.* 2000, Jerz and Rimstidt 2003), but even these conditions vary greatly from an indoor environment. There is also extensive bias towards rock-forming and commercially valuable minerals (Hazen and Ausubel 2016), leaving a great deal of species left unstudied beyond their initial identification.

Yet there is some relevant literature available if one is persistent enough to find it. However, much of this research is unavailable to museum professionals and little is entering museum literature. This is due to lack of accessibility and awareness.

Inaccessibility

Most of the relevant knowledge is published in journals, many of which have not switched to open access and are thus unavailable to most museum professionals. Without institutionally provided access, one is faced with the unsustainable prices of one-off article purchases or organisational memberships. As it is, membership to museum organisations is expensive enough to detract people from subscription (Allington-Jones 2020), further reducing their chances of coming across relevant information. Books too are equally inaccessible, as these texts frequently have limited print runs, are out of print, or cost a small fortune to purchase.

In addition to *physically* being inaccessible, knowledge is also *verbally* inaccessible. Literature from other fields is laden with specific and technical jargon, strange graphs, and terrifying equations. Most museum professionals are overwhelmed by this and will avoid reading texts that are ‘too scientific’, regardless of the content’s significance. The lack of easily

digestible information tailored for a layman's understanding significantly hampers knowledge transference.

Lack of Awareness

Yet the largest obstruction of knowledge exchange comes from a lack of awareness. Many museum professionals are unaware that relevant knowledge *is* available from other sectors. And many researchers from other sectors are equally unaware of their findings' implications for museums and heritage (Emmons 1945: 88). Those who do acknowledge such uses fail to effectively communicate across disciplines, as their work is rarely advertised or published within museum literature.

This is why standards and guidelines are crucial. These documents are issued internationally (ISO), nationally (BSI), and by sector organisations, and provide information on how and *why* things should be a certain way. They are comprehensive texts based on scientific evidence that are also written in a simplistic and clear manner. Many have been written for the museum sector. However, the few available which address minerals and other geological materials (Brunton *et al.* 1984, Stanley 2004, BSI 2012) do not elucidate the matter of stability. They go on at length about acquisitioning, deaccessioning, and documentation, but generalise when discussing environmental conditions and their effects on specimens. Some suggestions made can actually be damaging to a number of sensitive minerals, but neither are such minerals and their ideal conditions defined anywhere in the text. The sole exception is pyrite and marcasite (Fig. 10). This highlights the uncertainty and confusion felt towards geological collections and their stability resulting from the lack of research (Baars and Horak 2018).

Relative humidity and temperature for the display and storage of geological specimens (I)

Specimens	Ambient Temperature (2)	Ambient Relative Humidity
General Guidance:	16-22°C	45-55%
Sensitive minerals and other materials (3):	depends on mineral or material	
Pyrites and Marcasite and fossils containing these minerals (4)	16-22°C	20-30%
Sub-fossil bone (5), tusks, teeth: fossils with shale or clay matrix (6)	16-22°C	not below 40%

Figure 10. A table from the MLA standards (Stanley 2004) depicting the recommended temperature and RH for different geological materials. The information conveyed is meagre considering the array of materials it encompasses. Nor does it elucidate what minerals are sensitive and how best to store them.

The literature has shown that while we largely know the general nature of degradation processes occurring to minerals in museum environments, we do not know the specifics. There is uncertainty as to what minerals are vulnerable. Without sufficient scientific evidence, the minerals previously identified as vulnerable may in fact be stable, and there is a great likelihood that there are additional species yet to be determined as susceptible to indoor conditions.

This lack of evidence means that predictions cannot presently be made. There is no means of identifying trends in deterioration across environments or mineral composition. Subsequently, we are unable to predict what minerals are likely to be vulnerable. Damage mitigation can only occur by knowing the risks. Thus, it is critical to study mineral reactions and their products to determine how much of a risk certain agents are to a given mineral species. This project aims to tackle some of these issues through the following methods.

3. Review of Methodology

3.1. Research Synthesis and Analysis of Mineral Stability Data

Research from various fields—including museums, earth science, chemistry, and material science—is systematically being reviewed to consolidate current understanding on mineral stability relevant to museum collections into one, conveniently accessible and interpretable database. This will aid data correlation and determination of mineral stability fields.

The current process involves searching for and reviewing relevant articles to find stability and reaction data for minerals at indoor conditions. This is more challenging than initially assumed. Locating relevant literature is a time-consuming task which unfortunately cannot be automated. However, in the first round of data collection, approximately 300 articles have been found to contain relevant information soon to be added to the database.

The current version of the database is an Excel spreadsheet containing entries for 468 minerals with references. Each entry includes a variety of fields (Fig. 11) including identifiers, stability parameters, notes, and citations. The information is ordered by Hey Index numbers—an organisational system which organises minerals according to their chemistry—rather than alphabetically, to facilitate an understanding of how related minerals are affected by a given agent of deterioration. The effects of temperature, moisture, light, and pollutants are presented side by side—rather than separately, like previous stability data (Parsons 1922, O’Donoghue 1983, Howie 1984, 1992a, Horak 1994, Hazen and Ausubel 2016)—to enable conclusions about the potentially synergistic effects of these agents. Also listed are the conditions at which unwanted changes may occur and the resulting alterations that may ensue from chemical and physical changes.

	A	B	C	D	E	F	G	H	I	J	K	L	M	
1	Mineral Group	Hey Number	Mineral Name	Chemical Formula	Temperature	Moisture	Light	Acids / Pollutants	Alteration / Disintegration	Hardness	Notes	References		
173	Halides	8.3.5	miersite	(Ag, Cu)I			surface reaction (darkens)					Nassau 1992		
174		8.4.3	bischofite	MgCl ₂ · 6H ₂ O		deliquescent (20C & 33%RH); dehydrates (25C & 3%RH); highly water soluble; store in sealed container			decomposes in air	1.5		O'Donoghue 1983; King 1992; Waller 1992		
175		8.4.5	carnallite	KMgCl ₃ · 6H ₂ O		deliquescent; dehydrates (32C & 3%RH); highly water soluble; store in sealed container; hygroscopic				2.5		O'Donoghue 1983; King 1992; Waller 1992		
176		8.4.6	tachyhydrite	CaMg ₂ Cl · 12H ₂ O		deliquescent; very hygroscopic; highly water soluble; store in sealed container				2.0		O'Donoghue 1983; King 1992; Waller 1992		
177		8.4.7	fluorite	CaF ₂	heat sensitive (very high)			colour change; fades			4.0; brittle		O'Donoghue 1983; Nassau 1992	
178		8.4.8	sinjarite	CaCl ₂ · 2H ₂ O		hydrates (25C & 11%RH); strongly hygroscopic							Waller 1992	
179		8.4.9	antarcticite	CaCl ₂ · 6H ₂ O	dehydrates (29.9C)		deliquescent (RT, 33%RH); dehydrates (RT, 21%RH)						Waller 1992	

Figure 11. A section of the mineral database, depicting the fields available and examples of the information contained.

However, the dataset has grown too large and complex for Excel, so other database programs are being reviewed. Microsoft Access was assessed but proved to be more unwieldy than desired. A relational database management system (RDBMS) using structured query language (SQL) is promising and is compatible with the internet coding languages. This is ideal as the database will ultimately be hosted on the project's website.

The Website

Reference for Mineral Care is the project's website used for publicizing the project and its findings. Its aim is to be a widely and openly accessible repository for the project's products. These include the database; research and experiment updates; reviews of literature, conferences, etc.; experimental data; open access versions of articles; and the links to any of the aforementioned if stored in ORA or ORA-Data. By doing so, the website addresses various requirements imposed by project funders—such as ensuring that research impacts are realised by making information openly accessible to practitioners—and meets a project aim. The domain has already been granted through the University Mosaic system and will be live by June 2020.

3.2. Collection Assessment

Assessments are used to determine changes of state (Ashley-Smith 1995) and the processes that cause such changes within a collection. Assessments are often the only time collections are systematically examined (Taylor 2005). Since assessments occur fairly infrequently—usually every ten years—a well-designed assessment method is required to capture as much relevant data as possible without being too time demanding. The results in turn

provide an improved understanding of a collection's condition and environment, and allows for better decision making and preservation strategies.

3.2.1. Review of Condition Assessment Methods

Condition assessments are a common tool employed throughout the museum sector. While the reasons for their application vary (Taylor and Stevenson 1999), these assessments record a collection's condition to identify causes of damage and aid decision making (Taylor and Watkinson 2003, Forleo and Francaviglia 2018, Kosek and Barry 2019). While appearing simple, the process is complicated by numerous variables which introduce variation to results and their interpretation. Be it the object, environment, surveyor, or means of documentation, each affects the reliability of data produced if not controlled or mitigated (Taylor and Watkinson 2007, Taylor 2013).

Previously developed methods used generic forms (Fig. 12) with broad and often ambiguous terminology in order to be applied to multiple or mixed media collections. However, such terminology introduces interpretational bias (Taylor and Stevenson 1999, Taylor 2013). If criteria are broad, overlap, or not well defined, their interpretation will vary as each person applies their own frames of reference to determine what the terms mean for a given context (Taylor 2013). Terms such as 'good' and 'bad'—which are commonly used for ranking condition (Ashley-Smith 1995, Taylor 2013, Gioventù 2018, Kosek and Barry 2019)—are subjective and qualitative. Most may know what contributes towards 'good' or 'bad' condition. But as there is no standardised definition for either term when applied to museum objects, each person will define them differently according to their past experiences and knowledge of the material being assessed (Taylor 2013). As such, terminology used should be clearly defined,

relevant, and mutually exclusive in order to increase reliability and objectivity (Sully and Suenson-Taylor 1996, Taylor and Stevenson 1999, Taylor 2013).

National Museum Condition Survey

Dept.		Location								
Date		Sub-location								
Identity no.	Description	Completeness	Integrity	General condition	Stability	Damage	Disfigurement	Cons. urgency	Storage conditions	Curatorial assess.

COLLECTIONS CONDITION AUDIT

Condition grades:
1: GOOD: Good conservation condition, stable
2: FAIR: Disfigured or damaged, no immediate action
3: POOR: Probably unstable, needs remedial work
4: UNACCEPTABLE: Actively deteriorating

Damage categories:
MAJor structural damage
MINor structural-cracked, bent, loose
SURFace flakes, crazing, lifting
DISFigurement - stains, scratches
CHEMical - acid paper, corrosion, rubber breakdown
BIOlogical - mould, insect, rodent
OLD - sub-standard repairs
ACCretions of dirt, grease, deposits

Survey code: Initials: Date:
2002-C SJK. 7.7.2002

Collection: COSTUME

Sub-collection: ACCESSORIES

Store: BH-TOP

Location: SC3 S4

Inventory no.	Object name	Materials	Tick								COND	Remarks	
			MAJ	MIN	SURF	DISF	CHEN	BIO	OLD	ACC			
1294-36	Hat	straw, silk	✓									3	
A5434	Hat	silk		✓								1	
A21052	Hat	Wool						✓				4	live with
A5549	Hat	Wool						✓				4	" "
A1890-154	Gloves	Leather		✓	✓							1	
1995-55	Gloves	Wool										1	

Figure 12. Examples of forms used for condition assessments. Form 1 (Taylor and Watkinson 2003) uses subjective, value-based terminology. Form 2 (Taylor 2013) uses terms more aligned with possible types of change, but there is still some uncertainty and overlap between the categories. In both forms, the surveyor is not noting down exactly what they see, but rather mentally going through a number of steps to determine if the change seen fits a given category. Categories such as these introduce variation, both by those performing the survey and by those interpreting the results. In turn, the reality may be quite different from what was documented.

Many assessment methods (Taylor and Stevenson 1999, Taylor 2013, Forleo and Francaviglia 2018, Gioventù 2018) focus on determining the causes of damage, rather than identifying the damage itself. This process again introduces interpretational bias (Taylor and

Stevenson 1999), as one is not just recording what is seen, but rather determining what caused the effects and then translating it into the categories of the form (Fig. 12). In addition, the causes are often difficult to determine, as they necessitate inferences and assumptions. This multistep thought process introduces variability by requiring additional information that is often not readily available (Taylor and Stevenson 1999, Taylor and Watkinson 2003), such as knowledge of environmental conditions, housing material, and how these react with objects. The surveyor may not fully or correctly understand these reactions or only search for the specific causes that confirm one's suspicions (Taylor and Stevenson 1999, Taylor and Watkinson 2003), resulting in attribution error and false data.

Even if the cause of damage is obvious when looking at the object, others may interpret it differently at a later stage if the cause is not accurately reflected in the form (Taylor and Stevenson 1999). An example is 'biological damage', which could be caused by either mould or pests. If there are no means to differentiate between specific types of damage, one may believe it to be one type when it actually is another. Yet, reliability can be introduced by recording the effects instead of the causes, as effects are easier to identify and document (Taylor 2013).

But determining which and how many criteria to record can be difficult. Forleo and Francaviglia (2018) based theirs on the ten agents of deterioration (Table 1), whereas others (Sully and Suenson-Taylor 1996, Kosek and Barry 2019) focused on a few phenomena indicative of stability. Taylor and co-authors (Taylor and Stevenson 1999, Taylor and Watkinson 2003) offer that only essential data should be collected. Although the exact number and terms used may vary, criteria should be specific, comprehensive, and well-defined to minimise subjectivity, enhance reliability, and accurately record condition without collecting unnecessary information.

3.2.2. Review of Risk Assessment Methods

While condition surveys are useful in assessing the present state of collections, they cannot predict potential changes to objects in the future. This is the role of risk assessments. Risk assessments are used to identify potential hazards to a collection and the likelihood of them causing damage (Taylor 2005, Baars and Horak 2018). This data is then used in the evaluation and prioritisation of risks, ultimately informing preservation and risk management strategies (Muething *et al.* 2005, Pedersoli *et al.* 2016, Cannon and Waller 2017).

‘Risk’ is the likelihood of an event occurring that results in damage. Damage only occurs, however, when an object is both susceptible and exposed to a risk (Pedersoli *et al.* 2016). It is important to estimate the likelihood (frequency) of a risk event occurring and the extent of its impact (often expressed as loss in value) in order to determine the magnitude of risk (MR). MR scores allow for a comparable evaluation of risks and prioritisation of those determined to be the most damaging (Muething *et al.* 2005, Pedersoli *et al.* 2016). Methods of calculating MR (Table 4) vary with the method employed (Waller 1994, Pedersoli *et al.* 2016), but each assigns values to 1) the risk’s likelihood, 2) the amount of value lost, and 3) the percentage of the object or collection affected by the risk within a given period of time (often 100 years).

Waller’s (1994) Cultural Property Risk Analysis Model (CPRAM) has additional complexity compared to the ABC method (Pedersoli *et al.* 2016). Defined risks are assigned to one of three categories of severity: 1) rare and catastrophic, 2) sporadic and severe, and 3) continuous and progressive. In addition, type 1 risks are given a different variable (P: probability) than types 2 and 3 (E: extent or rate) to reflect the differences in frequency and extent. Yet, by combining frequency and extent into one metric, not all risks fall neatly into these

three categories. Some risks may be continuous and catastrophic, sporadic and progressive, or even rare but mild.

Table 4. Two methods of calculating the magnitude of a risk. Although the formulas differ, each includes the same measurements of a risk’s likelihood and extent.

	ABC	CPRAM
Frequency	A	P
Rate		E
Value Lost	B	LV
Fraction of object/ collection susceptible	C	FS
Magnitude	= A + B + C	= P × FS × LV
		= E × FS × LV

At present, there is no meaningful way to quantify the uncertainty inherent to risk assessment results (Pedersoli *et al.* 2016, Cannon and Waller 2017). The uncertainty stems from the method’s predictive nature (Pedersoli *et al.* 2016, Cannon and Waller 2017), lack of research regarding deterioration processes in museums, and a limited understanding of how material change effects value (Waller 1994). As such, it is difficult to say how objective these risk assessment methods are due to the inclusion of ‘loss of value’. Value and its loss are contextual and observer-specific (Pedersoli *et al.* 2016, Cannon and Waller 2017), making objectivity difficult to obtain. Hence, it is often emphasised that risk assessment data is useful rather than precise, indicative rather than definitive (Cannon and Waller 2017). Thus, contextual information—such as floorplans, monitoring data, scientific research, and professional experience—is critical in improving the efficacy of risk assessments and enabling evidence-based predictions (Waller 1994, Muething *et al.* 2005, Pedersoli *et al.* 2016, Cannon and Waller 2017).

As a means of improving reliability, Taylor (2005) suggests combining the results of condition and risk assessments. The probable causes of damage identified in the collection assessment can be linked to those examined in the risk assessment. This provides a means of corroborating the likely exposure to and consequences of risks, and improves one's understanding of the deterioration and synergies occurring within a collection.

3.2.3. a Multiphase Approach for Mineral Collections

In an attempt to tackle the challenges of subjectivity, ambiguity, and variability, a multiphase approach has been designed to compare changes recorded in the literature to those presented in museum collections. The objectives are to:

- confirm alignment between literature and reality and if there are gaps in knowledge,
- identify the types of changes that occur to a given mineral species,
- determine which mineral groups are more susceptible to change,
- correlate patterns of changes to agents of deterioration.

What is **not** an aim of this assessment is determining whether a specimen is fit for a given use, has value, or is in 'good' condition. This is different from traditional assessment rationales (Taylor and Stevenson 1999). By not evaluating use, value, or condition, one can look at the state of specimens objectively, quantitatively, and without the bias or emotion that stems from some form of intangible loss. It is only when these aspects are removed that one can view signs of damage neutrally and use them as a means for better understanding the reaction processes occurring.

This multiphase collection assessment provides a detailed analysis of the types and likelihood of deterioration present in mineral collections, with the advantage of being specific to mineral groups. This specificity in turn allows for more tailored and focused management strategies of vulnerable mineral species.

Phase 1: Pilot Study

The aim of a pilot study is to test the methodology and determine if anything needs to be added, removed, or revised. It is a critical step (Taylor and Stevenson 1999) to ensure that the survey collects the required information in an efficient manner. During this phase, additional contextual information is recorded, including the environmental conditions, storage materials used, and how the minerals are stored together. This data is used to provide further context during data analysis (Taylor and Stevenson 1999; Taylor and Watkinson 2003).

Phase 2: State Survey

The state survey is designed to be quickly performed on a majority of the collection by simply noting which forms of deterioration are present or absent in a given specimen. Its aim is to determine which mineral species are represented in a given collection and what state these minerals are in through attributing phenomenological criteria (Table 5) to each specimen. In order to cover thousands of specimens, the criteria are limited and pre-defined. Only their presence or absence is noted—rather than determining extent and severity—to speed up the process, reduce variability due to interpretational bias, and solve the quandary of assigning quantitative values to a subjective perception (Cannon and Waller 2017). Cause of damage is

attributed during data analysis instead of during the survey to minimise distraction, interpretational bias, and attribution error.

Table 5. Criteria chosen for the state survey and their definitions.

Criteria		Definition
Surface	Corrosion	Voluminous and or platy products form on mineral surface; may be localised around a pit or crack; may extend across wide area of surface, forming a uniform layer; texture may be smooth, powdery, sandy, or flaky
	Efflorescence	Crystalline growth on surface and or within cracks
	Pitting	Small (relative to diameter) dents in the mineral surface; depth may vary
	Tarnish	A coating on the mineral surface; coating may be darker, metallic, iridescent, or different colour than the original colour of mineral
	Wet	Slick or damp to the touch; moisture may or may not be visible on surface
Body	Breakages	Distinct pieces have come away from the main body differs from flaking in that the pieces are thicker and more three dimensional differs from crumbling in that the breaks are usually clean and sharp
	Cracking	Splits in the mineral surface; can be of various length, widths and depths, but does not go completely through the specimen (depth-wise)
	Crumbling	Mineral falling apart into many round, distinct pieces, usually of various sizes
	Delamination	Mineral surface removed in distinct, leaf-like sheets; denotes sheets free from or loosely attached to the mineral body
	Flaking	Mineral surface removed in distinct, angular pieces; denotes flakes free from or loosely attached to the mineral body
	Powdery	A layer of grit covers the mineral surface; often comes away on glove with touch & found at base of container; grit ranges from fine & smooth to sand-like clumps
Colour	Change	Mineral colour altered from one distinct colour to another distinct colour that is not white or black (i.e. blue to yellow)
	Loss	Coloured transparent & translucent mineral is less vivid or colourless
	Lightening	Coloured opaque mineral is a lighter shade of that colour or white
	Darkening	Coloured mineral is a darker shade of that colour or black
	Opacity	Mineral has become translucent or opaque; may or may not involve a change in colour

The state survey is unique as many condition assessments do not survey most of the collection, but only a small, statistically representative subset (Sully and Suenson-Taylor 1996, Glud and Johnsen 2002, Forleo and Francaviglia 2018, Gioventù 2018). Also, the phenomenological approach is rare (Sully and Suenson-Taylor 1996, Kosek and Barry 2019), and even rarer is the omission of extent and severity.

Phase 3: Condition Assessment

More akin to the traditional condition assessment, this version employs random sampling to produce a subset of specimens to undergo more detailed analytical assessment. Quantitative data is produced through photography, weight measurements, and other analytical methods. These methods are more objective than visual assessment alone (Strlič *et al.* 2013), and adds the rigour of the scientific method to better characterise the specimen's state (Taylor and Watkinson 2003).

Phase 4: Risk Assessment

A risk assessment rounds off the approach, providing a powerful understanding of the relationship between change and its likely causes. This is accomplished by the determination of risks present and the susceptibility of minerals groups to each. Unlike the ABC or CPRAM methods (Table 4), this risk assessment has removed the aspect of 'loss in value' and focuses on only the likelihood of occurrence and amount of change incurred. Foregoing value is in line with the rest of the assessment method—and research project as a whole—in an attempt to produce reliable, repeatable, and quantitative data.

3.3. Experimentation

The findings from the collection assessments and research synthesis will determine which mineral species will be examined further through experimentation. Upon deciding 5-10 species to work with, experimental methodology will be chosen according to their susceptibility to environmental conditions. The main types of experiments will likely be hydration, dehydration, light exposure, pollutant exposure, and reversibility testing. Experimental procedures would be based off those published in the literature and a refined version of the pilot study methodology (Royce 2019). Various analytical techniques will also be employed to quantify the presence and extent of change. This project's pilot study (Royce 2019) identified a number of successful and available techniques. These will be employed with refined methodologies, and other techniques will be tested as well (Table 6).

Table 6. Techniques used in the research's pilot study and additional methods considered for assessment.

	Imaging	Spectroscopy	Other
Previously Employed	Colour Photography	Fourier Transform Infrared Spectroscopy (FT-IR)	Colorimetry
	Micro-Computed Tomography (μ CT)	Raman Spectroscopy	Weight measurements
	Scanning Electron Microscopy (SEM)	X-ray Diffraction (XRD)	
	X-radiography	Energy Dispersive X-ray Analysis (EDX)	
Techniques to Test	Laser Scanning	X-ray Fluorescence (XRF)	
	Digital Image Correlation (DIC)	X-ray Absorption Near-Edge Structure (XANES)	
	Environmental Scanning Electron Microscopy (ESEM)		

The pilot study (Royce 2019) was a feasibility test for sample acquisition, experimental methodology, and analytical methods used to detect dehydration-induced change. Samples of melanterite ($\text{Fe}^{2+}\text{SO}_4 \cdot 7\text{H}_2\text{O}$) and chalcantite ($\text{Cu}^{2+}\text{SO}_4 \cdot 5\text{H}_2\text{O}$) were successfully grown from supersaturated solutions of ferrous and cupric sulfate, respectively. These were then placed inside an environmental chamber at 30°C and 35%RH. These conditions are well past melanterite's stability curve, but only just on chalcantite's (Chou *et al.* 2002). The melanterite dehydrated while no changes were observed for the chalcantite samples.

The samples were analysed before and after the experiment. All analytical methods tested (Table 6) detected change to the melanterite samples, while only weight measurements were able to detect minor water loss to the chalcantite samples. XRD (Fig. 13) and Raman (Fig. 14) analysis of the melanterite dehydration product identified it as rozenite ($\text{Fe}^{2+}\text{SO}_4 \cdot 4\text{H}_2\text{O}$), and XRD also detected some amount of szomolnokite ($\text{Fe}^{2+}\text{SO}_4 \cdot \text{H}_2\text{O}$) in a sample.

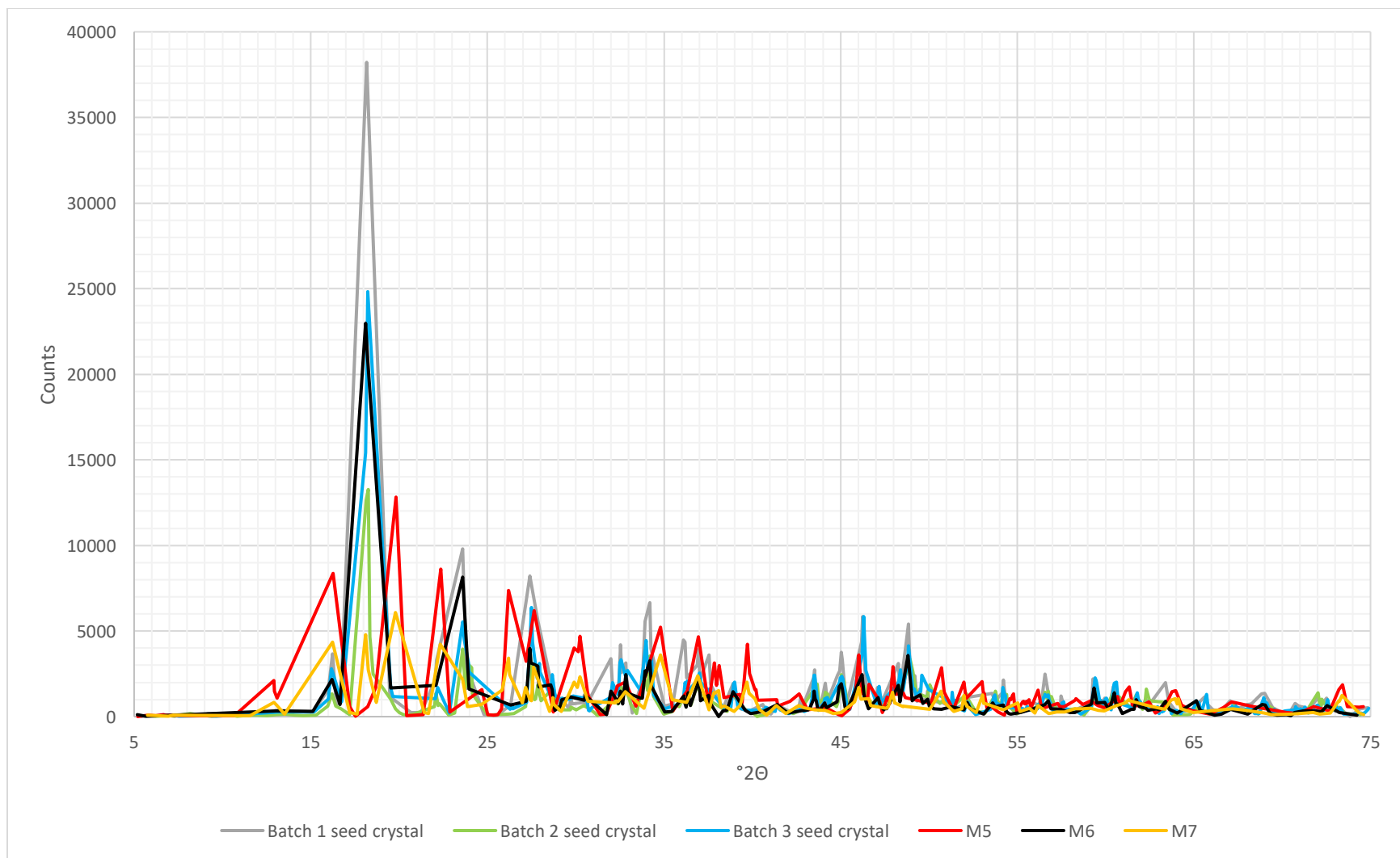


Figure 13 XRD spectra for the melanterite seed crystals, dehydrated samples (M5 & M7), and a control sample (M6). The profiles of the seed crystals and M6 are well matched to each other and to melanterite reference spectra. The peaks for M5 and M7 vary significantly from the other four spectra. Whilst M5 and M7 appear similar to each other, M7 has additional peaks which correspond to melanterite and szomolnokite. M5 and many of M7's peaks correspond to rozenite.

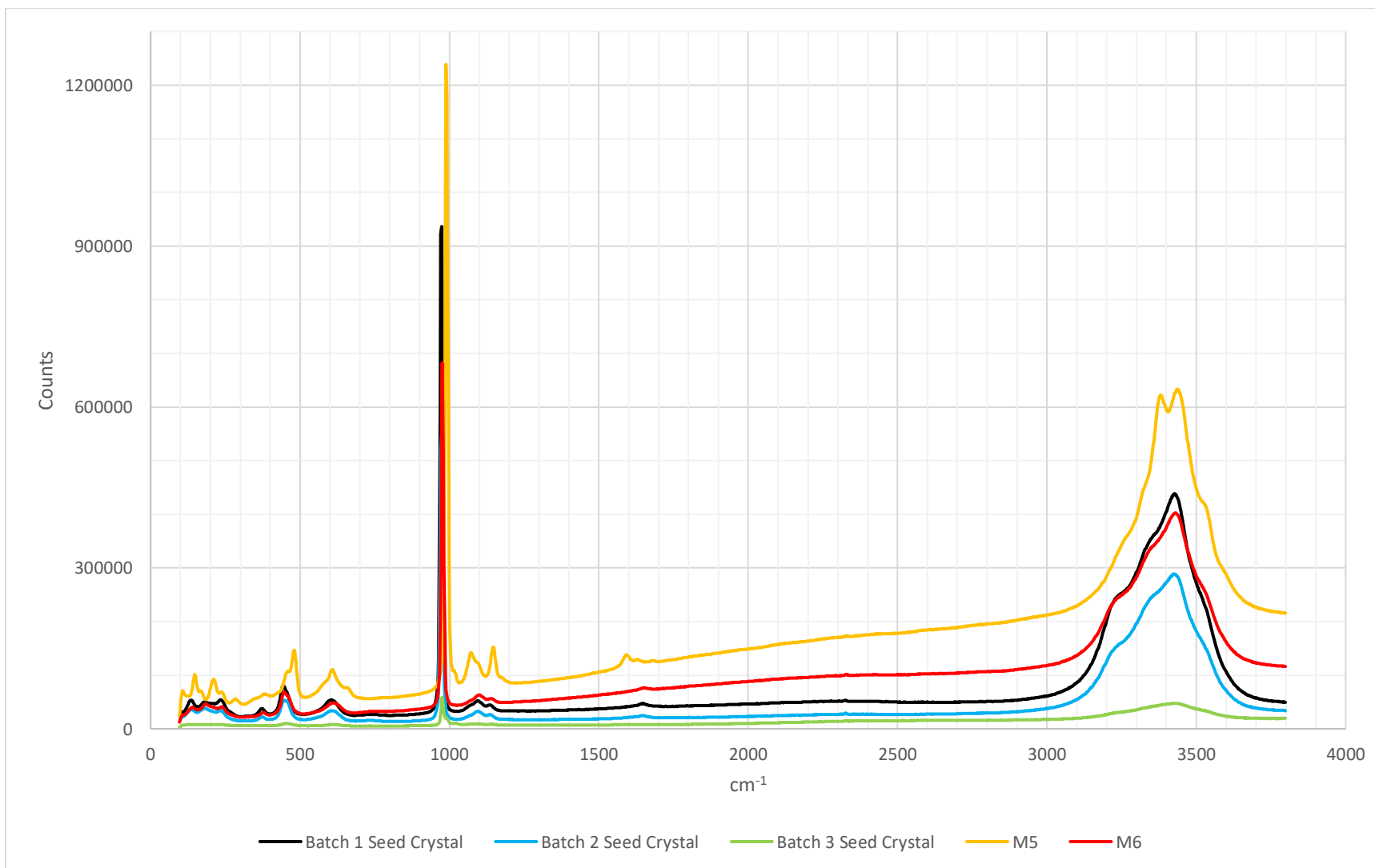


Figure 14. Raman spectra for the three batches of melanterite seed crystals, M5 (dehydrated sample), and M6 (control sample). All save for M5 are in good agreement with each other and are attributed as melanterite. M5, on the other hand, displays additional peaks and slight shifts in peak positions in line with the spectra for rozenite.

4. Progress to Date

Research Synthesis

- Designed first version of mineral database as Excel spreadsheet.
- Began reviewing references relevant for database from mineralogy journals; 70 of 300 have been read and data will be added to database.
- Applied for and granted Mosaic website through the university. Currently designing and will go live by June 2020.

Collection Assessment

- Designed collection assessment methodology to minimise pitfalls of previous assessment methods.
- 27.02.2020 - Performed pilot for state survey at NMC in collaboration with museum staff; deteriorating specimens from reserve collection used.

Communication

- Conferences
 - SPNHC & ICOM NATHIST joint meeting 2020—Edinburgh, Scotland
 - Workshop—accepted; approached by peer (Lu Allington-Jones) to act as co-organiser; 20 min. presentation on mineral instability
 - Poster—tbc; on design and rationale of multiphase collection assessment
 - Mineralogy and Museums 9 2020—Sofia, Bulgaria
 - Presentation—accepted; on creation of database of vulnerable minerals
- Talked to relevant experts

Skills Training

- Project-relevant: audited Crystal & Minerals lectures in Department of Earth Sciences; XRD training
- Transferable: *Statistics Fundamentals* 3-part course (LinkedIn Learning), MySQL introduction course (IT)
- Communication: paper writing skills (OxRBL); with general public (elevator pitches, for *The Conversation*; SSD); Open Access & Copyright (Bodleian iSkills)

5. Thesis Structure

Currently, I am aiming to complete the thesis via the paper route. The project lends itself to producing a number of papers, written upon the completion of phases or major tasks. Papers from the research synthesis and experiments will be submitted to mineralogical journals (i.e. *Geochimica et Cosmochimica Acta*). On the other hand, papers resulting from collection assessments would be more practitioner-oriented, and thus be submitted to museum and conservation journals (i.e. *Studies in Conservation*).

Chapter 1: Introduction

1.1. Aims & Objectives

1.2. Terminology & Definitions

Chapter 2: Literature Review

2.1. Minerals & Museum Collections

2.2. Mineral Instability & Damage

2.3. Factors Affecting Mineral Stability

2.4. Measuring & Monitoring Mineral Instability

2.5. Gaps in Knowledge & Research Needs

Chapter 3: A Database of Mineral Instability for Museums

3.1. Rationale & Design of Methodology

3.2. Key Findings & Trends (paper 1)

3.3. Areas for Further Research

Chapter 4: Museum mineral Collection Assessment

4.1. Rationale & Design of Methodology

4.2. Results of Collection Assessment at NMC

4.3. Results of Collection Assessments at Other Museums

4.4. Discussion of Results from all Collection Assessments Performed (paper 2)

Chapter 5: Experimental Investigations of Mineral Instability

5.1. Effects of Temperature Fluctuations

5.2. Effects of Inappropriate & Fluctuating Relative Humidity (paper 3)

5.3. Changes Induced by Photochemical Reactions

5.4. Effects of Gaseous Pollutants

Chapter 6: Discussion & Conclusions

6.1. Minerals Determined to be Unstable

6.2. Noteworthy Patterns & Trends

6.3. Implications for Collection Management & Care

Appendix: Standards document for managing museum mineral collections

- first in-depth standard on storage and display conditions required by mineral species, backed by scientific evidence; published at end of/after DPhil

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