University of Oxford – School of Geography & the Environment

Confirmation of Status Report

Assessing the Stability of Mineralogical Collections in Museums

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1. Introduction

"A problem which frequently confronts a museum curator is the proper preservation of certain choice specimens of minerals." — A.L. Parsons (1922: 59)

Minerals are the building blocks of rocks and fossils, and are the raw products for a variety of objects common to our daily life (Fig. 1) (Emmons 1945). Minerals have been used since prehistory (Whittle 1996, Renfrew 2013) to create pigments, monuments, structures, and a wealth of objects, such as pottery, metalwork, and jewellery. As such, minerals are ubiquitous throughout museums and heritage sites.

Figure 1. A display at Field Museum (Chicago, IL, USA) showing various minerals and their resultant products. These include currency, medication, nails, and toothpaste.

The prevalence of preserved mineral-derived objects, however, has fed into the popular assumption that minerals are inherently stable. While indeed, minerals and the objects made from them are relatively more stable than those derived from organic materials (especially if focusing on a human timescale), minerals are not immune to entropy and will be subjected to deterioration eventually.

The first publications discussing mineral instability within the museum context appeared in the first half of the 20th century (Parsons 1922, 1926, Bannister 1937). Yet as Parsons' (1922) opening line (above) suggests, mineral instability has been a long-standing and bemoaned issue. Parsons hoped that by discussing the occurrence of unstable minerals, he could "stimulate a study" (Parsons 1922: 62) of mineral stability parameters within the museum context. Fortunately, interest and examination of mineral instability grew within the museum sector throughout the 20th century, culminating in an intensive period of research from the mid-1970s through to 2000 (Howie 1979, 1984, 1992, King 1985, Waller, *et al.* 2000). While the quantity of information and discussion on the topic has greatly increased throughout the past century, many questions regarding best practice for mineral collection care have remained unanswered to this day (Waller, *et al.* 2000, Baars & Horak 2018). This doctoral project is a response to such calls for further examination of mineral instability within the museum context.

1.1. Project Summary

This project is part of the Science and Engineering in Arts, Heritage, and Archaeology Centre for Doctoral Training (SEAHA CDT), and is funded by the Engineering and Physical Sciences Research Council (EPSRC), the Pilgrim Trust, the Barbara Whatmore Charitable Trust, and the National Conservation Service (NCS).

Each SEAHA project is a collaborative initiative between academia, heritage, and industry, and has at least one partner from each sector. Projects are co-created by the partners to answer specific questions and problems currently faced by members of the heritage sector. This project in particular is formed of five partners: the University of Oxford, National Museum Cardiff (NMC), National Museums Liverpool (NML), OR3D, and BSRIA Ltd. The project remit stems from the lack of knowledge of the behaviour of geological materials in museum environments, and was proposed as a means of rectifying this lack by beginning the scientific studies required in order to bring current understanding up to par with that for other heritage material types, such as paintings, ceramics, paper, and archaeological finds.

Narrowing the scope was required to design an effective doctoral project. This was primarily done by limiting the research to minerals. While 5,828 unique mineral species have been approved by the International Mineralogical Association (2022) as of July 2022, not all mineral species can persist within the museum environment, due to requiring substantially different temperatures and or pressures to exist. Additionally, many, if not most, mineral species are not represented in museum collections. Over half of known mineral species are considered rare (i.e., are documented to occur in five or fewer localities), and many newly identified species only form at the micro- or nano-scale and were discovered during experiments utilising high-resolution microscopy and spectroscopy (Hazen & Ausubel 2016, Lee & Guo 2022). Taking these factors into consideration, approximately 2,000—or roughly one-third—of all known mineral species are likely relevant to museum contexts.

1.2. Aims & Objectives

A review of pre-existing literature (Royce, *et al.* 2021) illustrates that most information on mineral stability is generated by disciplines such as earth sciences, chemistry, and material sciences. However, the majority of this research in unavailable to museum professionals, both physically (due to the lack of open access publications) and verbally. For many museum professionals, literature from other fields may appear laden with specific and technical jargon, strange graphs, and terrifying equations. It is undeniable that these can overwhelm and confuse even the most scientifically inclined if they are unfamiliar with the subject being presented (Hoyles 2020). Thus, the lack of easily accessible and digestible information tailored for a layman's understanding significantly hampers knowledge transfer into the museum sector. Yet the largest obstruction of knowledge exchange comes from a lack of awareness and effective communication (Tennent 1994, Viñas 2002, Henderson 2018), as many museum professionals are unaware that relevant knowledge *is* available from other sectors.

Thus, the aims of this project are to:

1.) raise awareness that minerals are indeed subject to change and most forms of change can be mitigated or managed, and
2.) begin addressing the lack of accessible information on mineral instability within the heritage sector.

These are achievable through the following objectives and methods (Table 1).

Table 1. Summary of the project's three objectives, and the methods and outputs associated with them. Hyperlinks will direct the reader to either the relevant section of this report or to the respective webpages on the project website, Reference for Mineral Car.

Objective	**Method**	**Output**	**Thesis Paper #**
Identify which minerals are unstable within the museum context and the parameters which induce instability	Data Collation and Synthesis	the Mineral Stability Database	1
	State Survey	Survey of entire OUNHM mineral collection	3
Establishing low cost, easy-to-use methods that facilitate the identification of change in mineral specimens	State Survey	Survey of pyrites & marcasites at four different museums	4
	Colorimetry	Colorimetry Validation Experiment (CVE)	2
	Machine Learning	PyrΔTE	5
Sharing of information accrued during the project in order to make effective change within the sector	Digital Communications	Reference for Mineral Care	—
	Publications	Articles	1-5
	Verbal Communications	Conference Presentations & Posters	—

2. Summary of Methods

2.1. Data Collation and Synthesis

Hundreds of scientific publications were reviewed to create a comprehensive database—The Mineral Susceptibility Database (MSD)—that museum professionals can use as a reference when assessing the conditions required by their collections.

The Database began as a project to collate the data from Howie 1992 into one spreadsheet, rather than flipping back and forth between pages. The spreadsheet soon grew to include data from other publications which contained similar tables and data (Parsons 1922, 1926, Bannister 1937, King 1982, 1983, 1985, O'Donoghue 1983, Howie 1984, Hazen & Ausubel 2016). While these publications created a list of over 400 mineral species, much was left to be desired in terms of quantifiable information, such as reaction conditions, pathways, and products. Further consultation of the literature—especially the geosciences literature—was needed.

2.1.1. Literature Acquisition

The following four-step process (Fig. 2) was used for acquiring literature.

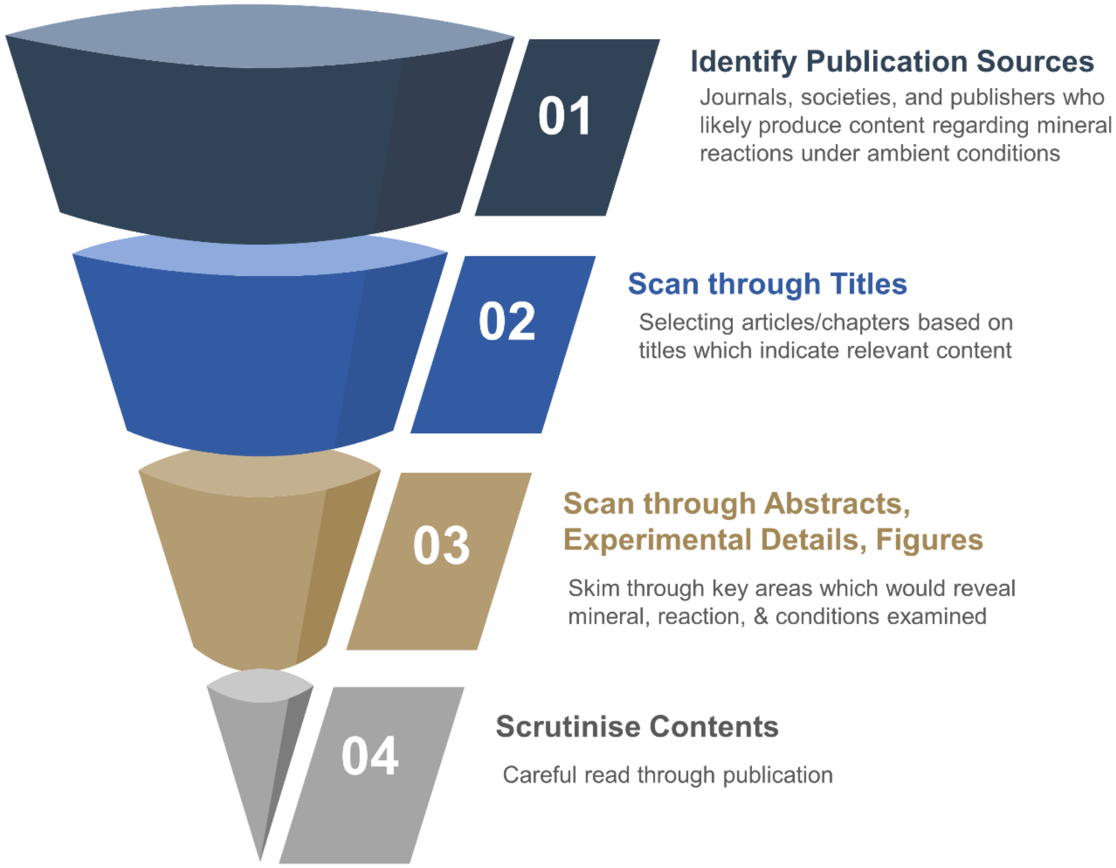

Figure 2. A graphical summary of the literature acquisition process for the MSD.

1.) **Identify Publication Sources**

Over a dozen journals and the publication series *Reviews in Mineralogy and Geochemistry* were initially identified as containing information relevant to mineral alteration under surface environments. Five of these journals—*American Mineralogist, Australian journal of Mineralogy, Journal of the Russell Society, Minerals,* and *Studies in Conservation*—were selected as the first to review.

2.) Scan through Titles

For the five journals selected, all issues from volume 1 through to the current publication (as of summer 2020) were scoured for titles which suggested study of minerals at surface conditions. Additional articles were amassed through citations found within—or via the 'Recommended' or

‘Related’ sidebars on ResearchGate, Academia, and publisher websites of—publications which had met the search requirements.

Keyword searches, especially within the geoscience literature, proved difficult for two reasons. Firstly, mineral instability covers a whole gamut of reaction types induced by a variety of agents. And secondly, due to the shear breadth of the English vocabulary, there are a great number of ways to phrase these reactions. Some ways are more preferable to others in a given sector, but no one way is standardised. This variety is most clearly and easily evidenced by the following selection of titles (Table 2).

Table 2. Example of titles for articles which are cited in the MSD, and a summary of the articles’ contents.

Title	**Content**	**Reference**
Water, sulfur dioxide and nitric acid adsorption on calcium carbonate: A transmission and ATR-FTIR study	The hydration of calcium carbonate (calcite) and how the hydrated layer affects the surface-pollutant reaction	(Al-Hosney & Grassian 2005)
Red lead darkening in wall paintings: natural ageing of experimental wall paintings versus artificial ageing tests	How water and sulfuric acid affect lead oxides (massicot and minimum)	(Aze, *et al.* 2007)
Nature of the alterations which form on pyrite and marcasite during collection storage	Oxidation of iron disulfide (pyrite & marcasite) and what affects the hydration state of these products	(Blount 1993)
Acquisition and evaluation of thermodynamic data for bieberite-moorhouseite equilibria at 0.1 MPa.	How moisture availability (humidity) affects the hydration state of hydrated zinc sulfates	(Chou & Seal 2005)
Natural fading of amethyst	Light-induced colour loss of amethyst (purple variety of quartz)	(Currier 1985)
A method for removing iron oxide coatings from minerals	Iron oxide (hematite & goethite) dissolution by sulfuric acid	(Drosdoff & Truog 1935)

None of the above example titles share similar keywords or phases. Additionally, the whole title is often needed to make sense of the content. This is because most titles addressing mineral reactions are structured in a very similar way:

Mineral Name or Group + Reaction + Conditions

But because each of the elements can be replaced with hundreds (if not thousands) of unique terms or phrases, the permutation of all possible keyword searches is near limitless. Thus, it was deemed wiser and easier to review pre-existing titles then try to guess which combinations of keywords and phrases would produce useful search results.

3.) Scan through Abstracts, Experimental Details, & Figures

Upon identifying articles by their titles, publications were then progressively weeded out by examining the abstract and experimental design. Like with the title, the three elements were sought for, with particular emphasis on the conditions. If the experiment was performed under atmospheric conditions, the rest of the paper was then scrutinised.

4.) Scrutinise the Contents

Due to the nature of the rejection process, it is difficult to determine how many publications were rejected in the first three phases. However, about 500 publications were selected for further scrutinization, which involves a closer reading of the paper. About 200 publications have been rejected at this stage. Another 200 met all requirements, and key data, quotes, and reaction processes were then inserted into the database. The remaining 100 have yet to be reviewed in addition to other publications subsequently identified as potential resources.

2.1.2. Database System and Organisation

The current version of the database is an Excel spreadsheet containing entries for 596 minerals with references. Each entry includes a variety of fields (Fig. 3) 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, 1992, Horak 1994, Hazen & 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.

Hey Number	Mineral Name	Chemical Formula	Conditions	Response	Appearance	Alterations	References
7	Oxides & Hydroxides						
7.3.1	cuprite	Cu_2O	light	photodecomposition	darkens	copper liberated	Nassau 1992
			light	surficial photo-oxidation	tarnish		Nassau 1992; O'Donoghue 1983; Howie 1984
			chlorides	oxidation & hydrolysis	colour change: pale green encrustation	to copper trihydroxychloride species	Sharkey & Lewin 1971; Scott 1990, 2000
7.4.7	periclase	MgO	moisture	tarnish	dull		O'Donoghue 1983
7.5.12	montroydite	HgO	light	surfical photo-oxidation	darkens		Nassau 1992
7.6.1	corundum	Al_2O_3	high light levels	colour change	yellow: fades		Nassau 1992
7.8.1	quartz	SiO_2	light, inc. sunlight	colour change (var. agate, amethyst, chrysoprase, citrine, morion, rose (crystalline), smokey)	fades		Currier 1985; Kane 1985; King 1985; Nassau 1992
7.8.8	opal	$SiO_2 \cdot nH_2O$	moist air	hydration			Howie 1984
			dry air &/or mild heating	dehydration	may show signs of shrinkage; cracks and loss of opalescence		Schumann 1977; King 1985
7.9.2	rutile	TiO_2	light	colour change	darkens		Nassau 1992
7.11.20	massicot	β-PbO	high RH	carbonation		to (hydro)cerussite	Aze et al. 2007
			sulfuric acid	sulfidation	yellow: black	to galena	Smith & Clark 2002
7.11.21	litharge	PbO	sulfuric acid	sulfidation	red: black	to galena	Smith & Clark 2002
7.11.22	minium	Pb_3O_4	sulfuric acid	sulfidation	red: black	to galena &/or other lead oxides	Smith & Clark 2002
			sulfuric acid	sulfidation		to platternerite & anglesite	Aze et al. 2007
7.11.23	plattnerite	PbO_2	acids				O'Donoghue 1983

Figure 3. An example of MSD Susceptibility entries for some oxide minerals.

However, the database has outgrown Excel, both in terms of size and usability. Other database programs were reviewed in 2020. Microsoft Access was assessed but proved to be more unwieldy than desired. A relational database management system (RDBMS) using structured query language (SQL) was deemed promising, primarily for its compatibility with internet coding languages. However, integration with the project website, *Reference for Mineral Care*, hosted through the University's Mosaic system would require further training in MySQL, R, and the R package Shiny. Due to the project's time restraints, this was put on the backburner in order to further other aspects of the project.

During the review of the first thesis paper (Royce, *et al.* 2021), which introduces the MSD, a reviewer suggested integrating the Database into a pre-existing entity, namely Mindat.org. When contacted about adding a stability section to their encyclopaedic pages, the chairman of Mindat replied that there was not the will nor the funding to pursue this at present.

Due to the nature of this response, efforts to improve the MSD were resumed. Recently, Notion (www.notion.so) has been identified as being a possible candidate for hosting the database moving forward, particularly for its database functionality. Notion pages can also be made into websites via Super (super.so). The feasibility of displaying the MSD as a Notion database is currently being trialled.

2.1.3. Summary & Outputs

- 987 entries for 596 mineral species (10% of total identified species)
- June 2020: piloted Access, MySQL, and Excel => Excel worked best at time
- June 2021: published MSD on *Reference for Mineral Care* & ORA-Data
- Summer 2021: Conference presentations - Goldschmidt 2021 & Mineralogy and Museums 9
- Spring 2022: Creation of mirror site (mineralcare.super.site) & trialling hosting MSD on Notion
- June 2022: Conference poster – SPNHC 2022
- Publication: (Royce, *et al.* 2021) - Thesis Paper 1; submitted with this report

2.2. State Survey

2.2.1. Background

Condition assessments are a common tool employed throughout the museum sector. However, as they occur fairly infrequently—usually every ten years, at best—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.

While the reasons for their application vary (Taylor & Stevenson 1999), these assessments record a collection's condition to identify causes of damage and aid decision making (Taylor & Watkinson 2003, Forleo & Francaviglia 2018, Kosek & 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 & Watkinson 2007, Taylor 2013).

Previously developed methods used generic forms (Fig. 4) with broad and often ambiguous terminology in order to be applied to multiple or mixed media collections. However, such terminology introduces interpretational bias (Taylor & 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 & 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 & Suenson-Taylor 1996, Taylor & Stevenson 1999, Taylor 2013).

National Museum Condition Survey										
Dept.		Location								
Date		Sub-location								
Identity no.	Description	Complete-ness	Integrity	General condition	Stability	Damage	Disfigure-ment	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: 2002-C Initials: SK Date: 7.7.2002
Collection: COSTUME
Sub-collection: ACCESSORIES
Store: BH-TOP
Location: SC3 S4

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

Figure 4. Examples of forms used for condition assessments; top (Taylor and Watkinson 2003), bottom (Taylor 2013).

Many assessment methods (Taylor & Stevenson 1999, Taylor 2013, Forleo & Francaviglia 2018, Gioventù 2018) focus on determining the causes of damage, rather than identifying the damage itself. This process again introduces interpretational bias (Taylor & 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. 4). 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 & Stevenson 1999, Taylor & 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 & Stevenson 1999, Taylor & 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 & 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 3), whereas others (Sully & Suenson-Taylor 1996, Kosek & Barry 2019) focused on a few phenomena indicative of stability. Taylor and co-authors (Taylor & Stevenson 1999, Taylor & 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.

Table 3. 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, artificial lighting
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

2.2.2. The Design of a New Surveying Methodology

A new approach to assessing the state of a collection was designed in an attempt to tackle the challenges of subjectivity, ambiguity, and variability. 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 material type or subtype,
- determine which materials are more susceptible to change,
- correlate patterns to agents of change.

What is **not** an aim of the survey 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 & 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 change neutrally and use them as a means for better understanding the reaction processes occurring.

The following survey method is an unique approach to condition assessment. Many pre-existing methods only evaluate a small, statistically representative subset of a collection (Sully & Suenson-Taylor 1996, Glud & Johnsen 2002, Forleo & Francaviglia 2018, Gioventù 2018) rather than its majority. Also, the phenomenological approach is rare (Sully & Suenson-Taylor 1996, Kosek & Barry 2019), and even rarer is the omittance of extent and severity.

This state survey is designed to be quickly performed on the whole or a fraction of a collection by noting which forms of change are present or absent in a given specimen. Its aim is to determine the state of objects through attributing phenomenological criteria to them. In order to cover thousands of objects, 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 & Waller 2017). Cause of change is attributed during data analysis instead of during the survey to minimise distraction, interpretational bias, and attribution error.

For this projects, specific criteria (Appendix 1) were chosen that visually indicate a change to a mineral. Not all are applicable to every mineral species, and some may be more indicative of deterioration than others. The presence of multiple deterioration phenomena (DP) is suggestive that deterioration has occurred. Whether that deterioration is active or not cannot be determined by visual observations alone and is out of the scope for the survey.

Certain combinations of DP suggest potential reaction types, such as surficial oxidation, oxidation at depth, pollutant-induced oxidation, efflorescence, surface wetting, and physical forces. These reactions can then be deemed first or second order depending on the percentage of specimens that exhibit these patterns; first order is a reaction that generally affects greater than 50% of specimens, whilst second order is that which affects less than 50%.

2.2.3. Summary of Progress

- Museum surveys completed (Table 4):
    - July 2021: National Museum Wales Cardiff (NMC; pyrite & marcasite only)
    - September 2021: National Museum Liverpool (NML; pyrite only)
    - April 2022: Sedgwick Museum of Earth Sciences, Cambridge (pyrite & marcasite only)
- In progress: Oxford University Natural History Museum (OUNHM; all minerals)
    - February 2021 – July 2022: 58 days, 11,048 specimens surveyed
    - Mineral groups completed: elements & alloys; sulfates & sulfosalts; halides; carbonates; sulfides; chromates, molybdates, & tungstates; iodates & borates; phosphates, arsenates, & vanadates; oxides & hydroxides; calcite; silica; neo-, soro-, & cyclosilicates
    - Ino-, phyllo-, and tectosilicates remaining

Table 4. Summary of specimens surveyed at the four museums, and the approximate age of each museum's collection.

Museum	Number of			Approx. Age of Specimens in Collection
	Specimens	Pyrites	Marcasites	
OUNHM	11,048	358	26	c.1790 – present
NMC	871	482	121	c.1850 – present
NML	136	135	1	c.1950 – present
Sedgwick	351	298	52	c.1650 – c.1900
Grand total	12,406	1,273	200	

2.3. Colorimetry

2.3.1. Background

Colorimetry is a valuable tool for many parts of the heritage sector, as it is an easy to use, increasingly affordable, portable, and non-destructive means of quantifying change over time within heritage contexts. It has been used to monitor and determine the effects of light (Bradley, *et al.* 2008, del Hoyo-Meléndez, *et al.* 2018), pollutants (Cabello-Briones & Mayorga Pinilla 2020), weathering (Benavente, *et al.* 2003, Iñigo, *et al.* 2004), and conservation treatments such as cleaning or consolidation (Bradley, *et al.* 2008, Pinto & Rodrigues 2014, Elnaggar, *et al.* 2015, Sansonetti, *et al.* 2015, Pelin, *et al.* 2016, Catenazzi 2017, Collado-Montero, *et al.* 2019) on a vast array of objects and materials. This includes, but is not limited to, artworks on canvas, paper (del Hoyo-Meléndez, *et al.* 2018), or papyrus (Elnaggar, *et al.* 2015); sculpture (Sansonetti, *et al.* 2015); mosaics (Cabello-

Briones & Mayorga Pinilla 2020); wall paintings (Catenazzi 2017, Collado-Montero, *et al.* 2019); building materials such as stone (Benavente, *et al.* 2003, Iñigo, *et al.* 2004, Prieto, *et al.* 2010, Pinto & Rodrigues 2014, Pelin, *et al.* 2016, Sammartino, *et al.* 2020), lime mortars, and limewashes (Gil, *et al.* 2011); fabrics (Kandi & Tehran 2010) and tapestries. Colorimetry has also been recently applied to herbaria specimens (pressed plants) (Sanmartin, *et al.* 2020), but remains underutilized for other natural (history) materials such taxidermy, fossils, and minerals. To determine additional applications within the natural history museum, research was conducted to verify possible use with geological specimens, specifically minerals.

2.3.2. Summary of Experimental Results

A series of colorimetric experiments were undertaken to critically evaluate colorimetry's application to mineral specimens within heritage collections. The performance of a Konica Minolta CM-700d and a Nix Pro 2 (Table 5) measurements of 2D colour cards and 3D mineral samples (Fig. 5) was assessed statistically and by resultant pseudo-object colours. A total of 9,600 data points collected was collected over three phases that occurred between October 2020 and March 2022.

Table 5. Reported specifications for the two colorimetric devices used during the experiment.

Model	Konica Minolta CM-700d	Nix Pro 2
Measurement Type	Reflectance	Reflectance
Dimensions	73 x 211.5 x 107 mm	60 x 60 x 42 mm
Weight	~550 g	43 g
Spectral Range & Interval	330-740 nm; 10 nm	–
Geometry	di:8°, de:8°	45°:0°
Specular Component	SCI & SCE	SCE
Measurement Area	SAV: 3 mm; MAV: 8 mm	14 mm
Aperture Diameter	SAV: 6 mm; MAV: 11 mm	14.5 mm
Mask Diameter	23 mm	20 mm
Repeatability	Spectral reflectance: Standard deviation within 0.1% Chromaticity value: Standard deviation within ΔE^*_{ab} 0.04	<0.1 ΔE^*_{00} on white (D50, 2° observer)
Inter-Instrument Agreement	Within ΔE^*_{ab} 0.2 (MAV/SCI)	<0.4 ΔE^*_{00}

Figure 5. Annotated image of the samples used during the experiment. Calcite 10 White and Mudstone Reverse not shown; both on reverse of respective sample. T: tumbled, R: rough.

The Nix Pro 2 proved to be suitable for the color cards. This colorimeter produced the best pseudo-object colors and also met many criteria for the heritage sector's ideal non-destructive equipment, most notably cost, size, and usability. This device, however, was the worst performer for mineral measurement, indicating that meters employing the d:8° optical geometry, like the CM-700d, still have the upper hand in terms of ability to measure a diverse range of materials.

Currently available portable spectrophotometers can be used to measure the color of opaque and metallic materials. Whilst there are some limitations in applying colorimetry to minerals (in terms of sample size and properties), it may be possible to employ colorimetry as a means of monitoring light-induced color changes and tarnish formation. Further research is necessary to confirm this, but initial experiments prove promising.

Additional information about the experiment can be found as thesis paper #2: *An Experimental Evaluation of Applying Colorimetry to Mineral Specimens* (attached with this report).

2.4. Machine Learning

Following the successful colorimetry experiment, a pilot study using pyrite colour and tarnish data was conducted to determine whether AI can be used to help identify change in museum specimens. This data was collected from hundreds of pyrite specimens from Oxford University Natural History Museum (OUNHM), National Museum Cardiff (NMC), National Museums Liverpool (NML), and the Sedgwick Museum of Earth Sciences. Nineteen volunteers helped to collect over eleven thousand data points (Table 6). Both the volunteers and the collections' curators also assessed whether each specimen was either tarnished or untarnished. This data was then handed over to the project partner, OR3D, who fed the data into two separate Regression AI modules in Python (TensorFlow and the Keras module) to identify patterns within the dataset. Here, the AI used the colour data to calculate tarnish likelihood and the overall colour difference.

The latest version of the calculator, dubbed PyrΔTE, was completed and released on the project website in June 2022. The PyrΔTE interface allows a user to input their own CIELAB colour values, either individually or as a series of data points in a .csv file. Whilst this programme is presently limited in scope to colorimetry and pyrite, PyrΔTE demonstrates that, with further development, similar AI tools can be created to aid identifying and treating visual and material changes to museum objects.

Table 6. Summary of data collected for developing PyrΔTE.

Museum	**Number of**		**Collector(s)**	**Dates of Collection**
	Specimens	**Data Points**		
OUNHM	247	8,752	volunteers, micro-interns	July 2021 – Mar. 2022
NMC	59	718	KR	July 2021
NML	33	354	volunteer	Sep. 2021
Sedgwick	47	627	volunteer	Apr. 2022
Other	3	699	volunteers, micro-interns, KR	Oct. 2020 – Mar. 2022
Grand Total	**389**	**11,150**	**20**	

3. Thesis Outline:

Section Title	Chapter Title & Summary	Thesis Paper #	Percent Completed (%)		
			Data* Collection	Data* Analysis	Writing
Front matter			—	—	**0**
Section 1: Introduction & Context	**Ch. 1 – Purpose, Value, & Use** - philosophical essay exploring a.) values of objects, b.) object-stakeholder interactions, c.) using objects for their intended purpose, and d.) object presentation and perception during exhibition and use	—	80	30	20
	Ch. 2 – Damage & Susceptibility - defines the terms 'damage' and 'susceptibility' within a heritage context	Part of 1	100	100	100
	Ch. 3 – Minerals as Collection Items - the typical 'literature review' section - a.) defines what the different types of geological materials are, b.) identifies the specific uses and values of geological collections, c.) introduces how these collections deteriorate within the museums setting through 'case studies', and d.) recounts historical perspectives and treatments to deterioration	aspects c & d part of 1	95	95	95
Section 2: Aims & Methodology	- at least 1 chapter long (**Ch. 4**) - outlines the project's a.) ontology and epistemology, b.) aims, c.) methods considered, d.) methods used, e.) limitations, and f.) effects of covid	—	100	100	50
Section 3: Experimental	**Ch. 5 – the Mineral Stability Database**	Part of 1	100	100	95
	Ch. 6 – Colorimetry Validation Experiment - briefly a.) outlines the use of colorimetry within heritage and on minerals, and b.) reports experimental findings	2	100	100	95
	Ch. 7 – State Survey at OUNHM - reports survey results at various levels: a.) collection-wide, b.) mineral group, and c.) mineral species of note	3	90	50	10

Section 4: Pyrite Specimens in Museum Collections	**Ch. 8 – Critical literature review of pyrite deterioration mechanisms** - further examines the possible oxidation pathways for pyrite within a museum context	—	50	20	20
	Ch. 9 – Results of Multi-Museum State Survey - a.) presents the findings from surveying the pyrites and marcasites at OUNHM, NMW, NML, & the Sedgwick, and b.) examines intervariable correlation within and across the museums	4	100	70	40
	Ch. 10 – Machine Learning + Colorimetry pilot - presents the a.) colorimetry data from the museum pyrite specimens, b.) human-performed data analysis, and c.) results of using an AI algorithm	5	100	80	20
	Ch. 11 – Unification of Data - attempt to determine how pyrite deteriorates in the museum context based on all data collected during project	—	85	30	0
Section 5: Discussion & Conclusions	**Ch. 12 – Discussion, Future Work, & Conclusions**	—	90	30	0

* data includes literature references & experimental results

4. Timetable to Completion

*Highlighted cells are months where work is actively being performed. Sep. 2022 is blank as that’s when I plan to take annual leave.

		2022					2023					
		8	9	10	11	12	1	2	3	4	5	6
	SS Data	Sedgwick analysis		finish OUNHM data collection	finish data analysis							
Writing	**CVE**	submit to journal		receive reviewer feedback	submit corrections /publication							
	SS - FeS2	start formally writing			revisions	submit to journal		receive reviewer feedback	submit corrections /publication			
	MLC			start formally writing		revisions	submit to journal		receive reviewer feedback	submit corrections /publication		
	SS - OUNHM				start formally writing		revisions	submit to journal		receive reviewer feedback	submit corrections /publication	
	Pyrite lit. rev.				review 'old' lit.	find & read 'new' lit.		start formally writing		revisions	submit to journal	
	thesis			rough draft			1st formal draft		2nd formal draft		final revisions	submission

Key:

Abbreviation	**Full Name**	**Additional Details**
SS Data	State Survey Data Collection & Analysis	Finishing off collecting data at OUNHM & completing data analysis
CVE	Colorimetry Validation Experiment	Paper 2 (submitted w/ this report)
SS – OUNHM	State Survey at OUNHM	Paper 3
SS – FeS2	State Survey of Pyrites & Marcasites	Paper 4
MLC	Machine Learning & Colorimetry	Paper 5
Pyrite Lit. Rev.	Pyrite Literature Review	Critical review of literature re. pyrite oxidation in museum-like environments.

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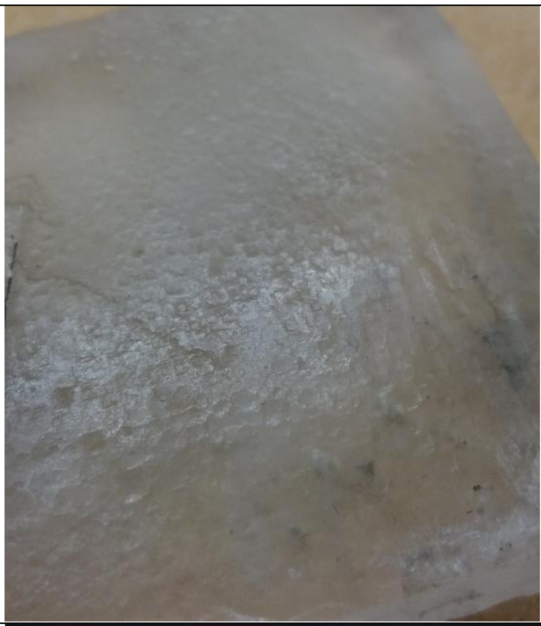
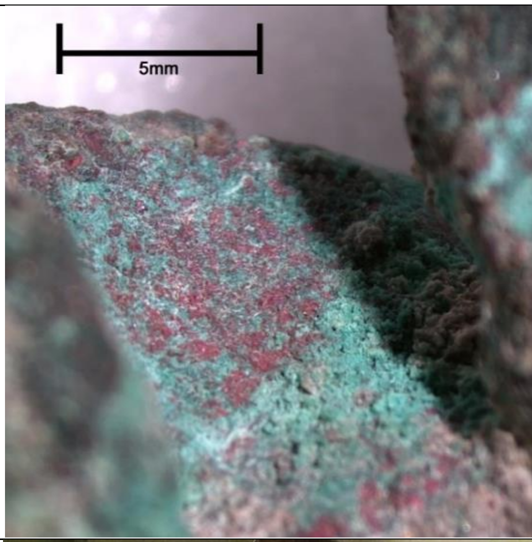
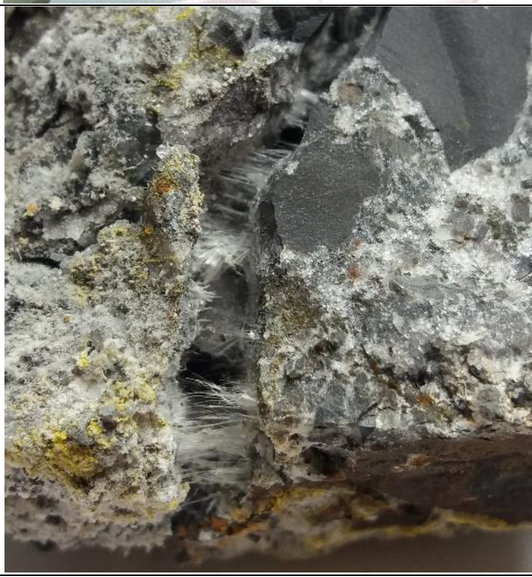
Appendix 1. Phenomenological criteria used during the state survey, with definitions and photographic examples.

Criteria Definition	**Example Images**
Dimpled Shallow divots in the mineral surface	
Rounded Mineral appears 'melted' with smooth edges	

<table>
<tr>
<td><u>Corrosion</u>
Voluminous amorphous products on mineral surface
May be localised or extend across a wide surface area</td>
<td>
</td>
</tr>
<tr>
<td><u>Tarnish</u>
A coating on the mineral surface
Coating may be darker, metallic, iridescent, or different colour than the original colour of mineral</td>
<td></td>
</tr>
<tr>
<td><u>Efflorescence</u>
Crystalline growth on surface and or within cracks of the mineral</td>
<td></td>
</tr>
</table>

Powder Amorphous grit covers the mineral surface • Often comes away on glove with touch	
Crumbling Mineral falling apart into many round, distinct pieces, usually of various sizes	
Flaking Mineral surface removed in distinct, angular pieces • Denotes flakes free from or loosely attached to the mineral body	

Breaks

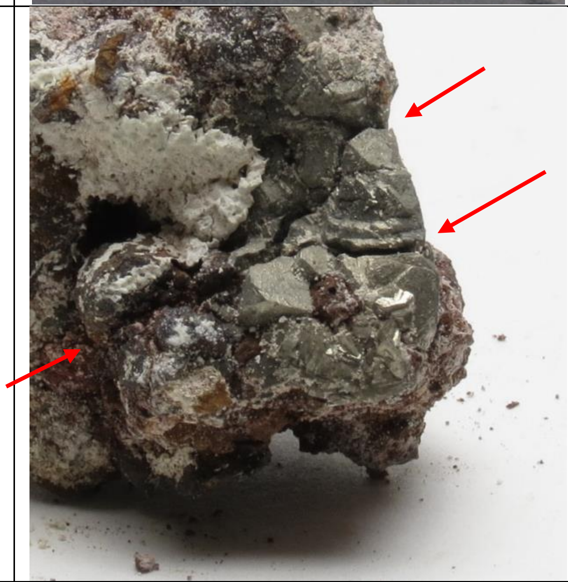
Distinct pieces have come away from the main body

- 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

Cracks

Splits in the mineral surface

- Can be of various length, widths, and depths, but does not go completely through the specimen (depth-wise)



Dull

Lustre of a mineral has changed or become absent (i.e., no shine)

- e.g., the finish of a metallic mineral has become sub-metallic or is no longer shiny

Dark Coloured mineral is a darker shade of that colour or black	
Pale Coloured mineral is a lighter shade of that colour or white/colourless	
Opacity Mineral has become 'clouded', translucent, or opaque	

Colour Change Mineral colour altered from one distinct colour to another distinct colour that is not white or black (e.g., blue to yellow), or has developed an iridescence	

Appendix 2. Project Outputs to Date

Publications

- Royce, K., Baars, C.B., and Viles, H. 2021. Defining Damage and Susceptibility, with Implications for Mineral Specimens and Objects: Introducing the Mineral Susceptibility Database, *Studies in Conservation*, DOI: 10.1080/00393630.2021.2015947
- Baars, C.B., Royce, K., and Cotterell, T. 2021. The importance of correct identification for the determination of appropriate storage conditions of minerals in geological museum collections. *The Geological Curator*, 11 (5), 355-360.
- Royce, K., and Baars, C. 2021. Caring for geological collections: unresolved questions. *Journal of Natural Science Collections,* 8, 28-38.

Conference Presentations & Posters

- Sep. 2022: SPPC 2022
- June 2022: SPNHC 2022
- Aug. 2021: Mineralogy & Museums 9
- July 2021: Goldschmidt 2021
- May 2019: SPNHC 2019
- Oct. 2018: NatSCA Conservation

Website: Reference for Mineral Care

- Original (Mosaic): https://mineralcare.web.ox.ac.uk
    - Regularly updated with Mineral Spotlights, blog posts, conference presentations, and publications
- Mirror (Super): https://mineralcare.super.site/

The Mineral Susceptibility Database

- *Reference for Mineral Care*
- ORA-Data

Appendix 3. Additional progress to date since Transfer of Status

Development of Subject-specific Skills

Attended:

- Mar. 2021: AI - theory and practical applications seminar (IT Learning Centre)
- Mar. 2021: GSECARS Virtual Tutorial on Crystal Truncation Rod Diffraction (University of Chicago)
- Apr. 2021: Virtual Workshop on Electron Probe Microanalysis (EPMA) developments and applications (Agricultural University of Athens)
- May 2021: Bayesian Reasoning for Qualitative Social Science (Department of Social Policy and Intervention)
- Nov. 2021: How to Write your Methodology Chapter (SSD)

Development of Professional Skills

- completed Statistics Fundamentals 3-part course (LinkedIn Learning)
- reviewed *Elementary Statistics* by Mario Triola to solidify statistics knowledge

Attended:

- Nov. 2020: Excel pivot table training (IT Learning)
- Feb. 2021: Postdoc Grant Writing & Applications seminar (SoGE D.Phil. training)
- June 2021: Goldschmidt pre-conference early career programme
    - Communicating Science
    - Learn about ERC Funding Opportunities
- Oct. 2021: Career Strategy Master Class (Careers Service)
- Oct. 2021: Understanding Job Descriptions (Careers Service)
- Jan. 2022: Writing Workshop – Scientific Articles & Thesis (SEAHA)
- Jan. 2022: Peer Review Workshop (Mineralogical Society)
- Apr. 2022: Making your Website Accessible (DHPSNY)
- May 2022: Digital accessibility: Practical solutions for digital content (IT Learning)
- May 2022: Digital accessibility: What is it ALT about? (IT Learning)

Other Relevant Events Attended

- Nov. 2020: Geological Curators Group mini seminar
- Dec. 2020: Sites at the Intersection of Cultural and Natural Heritage (SXNCH) keynotes
- April 2021: Narratives of disappearing & re-configuring heritage architecture in Japan (OUHN)
- May 2021: A future in ruins: Unsettling questions about heritage (OUHN)
- June 2021: CRYSPOM conference (Universite de Pau et des Pays de l'Adour)
- June 2021: The Emotion of Removal (Pitt Rivers)
- June 2021: Cultural Heritage in Crisis Situations conference (Department of Politics and International Relations)
- June 2021: Museums as "the true teachers of a free people" (Mansfield College)
- Oct. 2021: Team Pigment presentation (Bodleian Libraries)
- Oct. 2021: Decolonizing Museums conference (Center for Experimental Ethnography and the Penn Museum)
- Oct. 2021: The Brutish Museums book launch & panel discussion (Blackwell's)
- Feb. 2022: Colour and the Brain (St. Hilda's)
- Feb. 2022: PHILOSOPHY IN THE BOOKSHOP Anil Seth 'Being You' (Blackwell's)
- Mar. 2022: 'African Art as a Product of Neoclassical Thought' (TORCH)
- TT 2022: Nuffield Interdisciplinary Seminars on Empire
- June 27 & 28: Integrated Risk Management for Museums