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Research Article

Assessing the prevalence of glass alteration in natural history collection specimen storage

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Abstract

Glass plays a large role in the storage and preservation of natural history collections, from the jars and vials used to preserve specimens in fluid to the glass microscope slides holding thin sections and fragments. While the glass used for storing specimens is typically not considered part of the collection it houses, the condition and preservation of the glass directly impacts the long-term preservation of the collections as well as the time and budgetary resources of the museum. This is particularly true for large collections where consistent monitoring of the condition of every item is not realistic. The Glass Deterioration Working Group at the Smithsonian Institution conducted a survey of the condition of the fluid collections and microscope slides in the Department of Invertebrate Zoology at the Smithsonian Institution's National Museum of Natural History. Nearly a third of microscope slides, and over half of fluid collection containers were observed to have visible indications of glass deterioration.

Key words: Condition survey, fluid storage, microscope slides, wet collections

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Introduction

Glass is a widely used material for the storage of natural history specimens. The use of glass jars and vials to house fluid-preserved specimens has been common practice in natural history collections since the 17th century (Moore 1999; Simmons 2019; Dangeon et al. 2020). The use of glass is not only one of the more cost-effective options available for holding fluid collections, but it enables researchers to observe specimens without having to remove them from the containers and allows for fluid levels to be monitored and maintained (Palmer 1996; Simmons 2019). Additionally, many natural history institutions hold extensive collections of microscope slides used to both store and study specimens in greater detail (Neuhaus et al. 2017; Di Giacomo 2017). The Smithsonian Institution's National Museum of Natural History (NMNH) in Washington, D.C. houses the world's largest collection of natural history specimens across a wide range of disciplines from paleobiology to mineral sciences. Like other

natural history collections, a significant portion of the specimens in each of the museum's seven collecting departments are stored in jars or on microscope slides. While exact numbers are not available, it is estimated that NMNH makes use of over 1.7 million glass containers on shelves and over 6 million individual microscope slides (Fig. 1). These numbers continue to grow as new specimens are continuously added to the collection. Understanding the overall prevalence and impact of glass deterioration in these collections is critical to the long-term preservation of specimens. Storage glass is always being added to collections as older glass containers and microscope slides fail and are replaced and new specimens are acquired. Purchasing and managing storage glass can represent a significant burden on a museum's time and budgetary constraints.

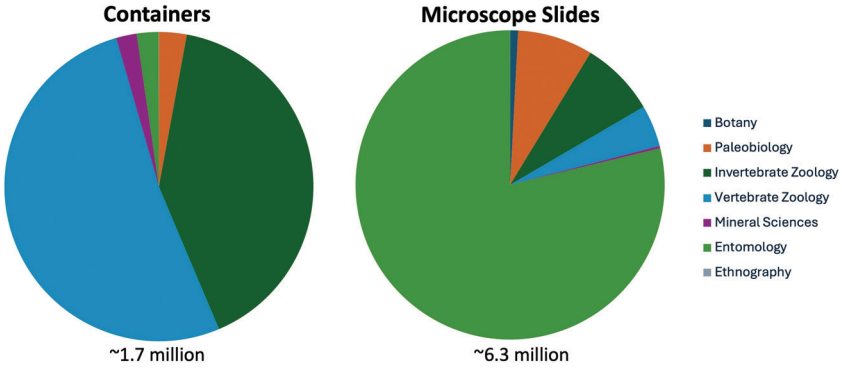

Figure 1. Graphics representing the estimated number of containers (left) and microscope slides (right) held across collections at the Smithsonian's National Museum of Natural History.

While the glass containers and slides themselves are typically not considered part of the collections that they house, the long-term preservation of the glass can directly impact the preservation of specimens. While several surveys of glass used in the storage of natural history specimens have been conducted in the past, most have focused very little, if at all, on the condition of the glass in these collections (Notton 1995; Palmer 1996; Thede 1996; Waller and Simmons 2003; Gütebier 2011; O'Hern et al. 2025). As part of a broader survey of glass in collections across the Smithsonian Institution, the Glass Deterioration Working Group recently undertook a survey of glass containers and microscope slides held in the Department of Invertebrate Zoology. This survey was aimed at quantifying the prevalence of glass deterioration issues found in both main forms of specimen storage glass (glass jars and microscope slides) and determining the impact of this deterioration on the preservation of collections at NMNH as a whole.

Glass alteration

Glass as a material is known to deteriorate in a number of different ways. The most common form of deterioration associated with glass is mechanical damage such as cracks or breaks. However, in museum environments, glass alteration can play a large role in the deterioration of glass and glass containing objects. Glass alteration is a form of deterioration that results from an ion exchange reaction between the alkali components present in a glass matrix and the hydrogen in

water or other hydrogen-bearing species in the surrounding environment (Kunicki-Goldfinger 2008; Majérus et al. 2020; Gin et al. 2021; Zanini et al. 2023). Over time, this reaction leads to the development of an altered layer on the surface of the glass that is often characterized by increased opacity or micro-cracking networks sometimes referred to as crizzling (Brill 1975; Koob 2006). These crack networks will continue to expand and develop over time and can eventually lead to fracture and fragmentation of the slide or vessel (Brill 1975; Koob 2006; Zanini et al. 2023). It is important to note that this increased opacity can be difficult to visualize in glass surfaces that are in contact with fluid. The formation of secondary precipitate materials on the glass surface, as the removed alkali reacts with the surrounding atmosphere, are also frequently observed on altered glass surfaces (Organ 1957; Kunicki-Goldfinger 2008; Majérus et al. 2020; Zanini et al. 2023).

In high humidity environments, these secondary precipitate products can deliquesce, resulting in the formation of liquid droplets on the glass surface (Organ 1957). The rate at which glass alteration occurs is dependent both on glass composition and on the environment in which the glass is held, with higher alkali contents and higher humidity environments both contributing to higher alteration rates (Kunicki-Goldfinger 2008; Majérus et al. 2020).

Glass jars and vials

The collections at NMNH make use of an estimated 1.7 million glass jars and vials in the storage of specimens, the majority of which are preserved in fluid. The fluids used in specimen preservation vary widely but are most frequently alcohol or formalin-based solutions (Simmons 1995; Finkelde and Newsome 2020). Caring for the specimens housed in fluid in the collection at NMNH is a complex task that involves a large number of specialized collections professionals who monitor these collections to ensure that specimens remain submerged, identifiable, and usable for scientific research (Friederichs 2020). Aging and deterioration of the gaskets or seals that are used in many of these containers, which can lead to fluid evaporation and specimen drying, is the most commonly cited preservation issue for these collections (Thede 1996; Van Dam 2000; Sablier et al. 2020; Dangeon et al. 2020). However, a less frequently discussed preservation issue for these items is the deterioration of the glass containers themselves (Sturm 2006; Kotrba and Golbig 2011; Simmons 2019).

In addition to occasional mechanical damage from handling and use, glass containers have been observed to exhibit visible glass alteration (Thede 1996; Simmons 2019). This glass alteration can present in several different ways in fluid storage containers. In the most advanced cases, the alteration can become so extensive that the glass jar or vial cracks into multiple pieces (Fig. 3A) (Hiebert et al. 2021). These cracks and breaks can have significant consequences including fluid loss leading to the contained specimens drying out or the separation of specimens from their identifying labels. If left unchecked, all glass alteration has the potential to eventually impact the structural integrity of the glass body. In less advanced cases, glass alteration often appears as either increased opacity or secondary precipitate growths on any glass surfaces not in direct contact with fluid (Fig. 3B–E). Additionally, the development of an iridescent layer on the fluid-contacting glass surfaces of glass containers has been previously noted

(Fig. 3G) (Simmons 1995). There is also concern cited in the literature about the potential of the alkali leached from the glass adversely impacting the contained specimens (Simmons 2019). The presence of the fluid inside of these containers corrects for much of the light scattering caused by any microcracking or crizzling as well as any iridescent surface layers, making visualizing altering glass in-situ extremely difficult. Both increased opacity and iridescence are most visible in jars that have been emptied of their contents and allowed to dry.

For the glass vessels used in fluid storage, not only does storage space environment play a role in alteration, but the contained fluids can impact alteration rates as well (Koob et al. 2018). In fluid collections, one or both faces of a glass vessel are in constant contact with an aqueous solution, effectively a 100% relative humidity (RH) environment, leading to a higher observed rate of alteration than might be expected for similar items aging under atmospheric conditions (Gin et al. 2021). Additionally, fluid composition and pH are thought to impact the alteration rates of glass surfaces (Gin et al. 2021).

The types of jars used in fluid storage collections vary considerably. Older collections often contain ground glass jars while others use glass jars and containers intended for the preservation of food, such as canning or pickling jars, which come in a wide range of sizes, shapes, and closures. More modern collections tend to make use of soda or borosilicate glass jars with plastic or metal screw top lids (Simmons 2019; Friederichs 2020). Additionally, to minimize space and keep related specimens together, many smaller collection items are stored in multi-level containment (e.g., inside of cotton-plugged vials that are themselves submerged inside of larger jars). For the purposes of this project, the term 'jar' is used to refer to the outermost glass container (in contact with the shelf) and the term 'vial' is used to refer to any smaller glass vessel submerged inside of another container regardless of the shape of the vessels being considered (Fig. 2).

While the glass containers used for storing natural history specimens are themselves typically expendable and usually replaced when issues with their functionality are noted, the enormous number of containers spread out of over miles of shelving makes frequent monitoring of their condition unrealistic. Sourcing glassware that is appropriate in shape and volume for the intended collection items, particularly for larger specimens where a wide mouth jar may be required, can be challenging and expensive, especially if bespoke jars are

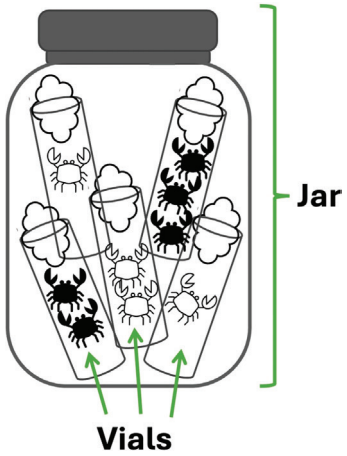

Figure 2. Diagram illustrating a primary container or 'jar' with internal 'vials' containing specimens.

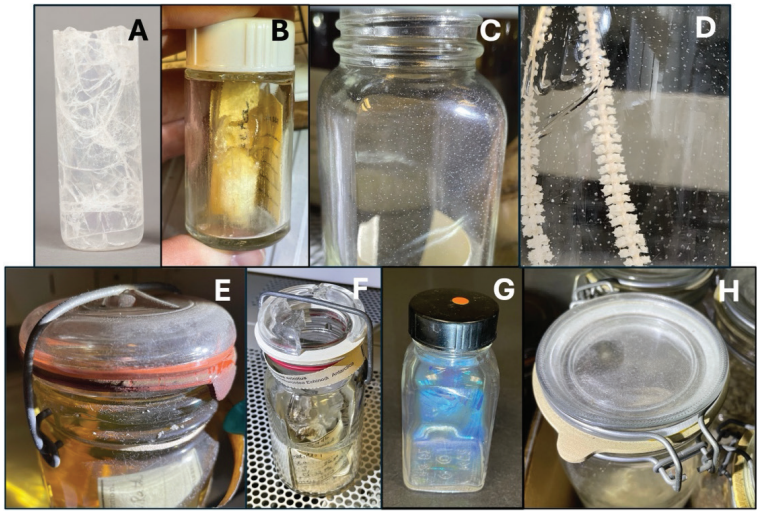

Figure 3. Images of containers found in the fluid storage collection of Invertebrate Zoology with a range of visible deterioration phenomena: **A** an internal vial that was removed from the Invertebrate Zoology collection that has experienced advanced glass alteration and cracking, **B** small jar with increased opacity of the glass, **C, D** jars with secondary precipitate products (white dots) on the external surface of a glass jar (**D**: USNM 1116838), **E** a jar with increased opacity on the glass components that is difficult to distinguish from surface debris, **F** a jar with non-alteration related mechanical deterioration (USNM E48621), **G** an emptied jar with an iridescent surface on the internal face, **H** a jar that is covered in dust.

needed. Even when condition issues are noted, jars are frequently kept in service due to the cost and difficulty of replacing them. When purchasing jars, collections representatives often must balance quantity and quality (e.g. borosilicate or soda lime glass) with available funds.

Microscope slides

There are an estimated 6.3 million individual microscope slides held across NMNH Departments (Di Giacomo 2017). These slides house a wide range of different formats of samples, from histological sections to entire organisms. While extensive work has been focused on the preservation of these items for use in research, much of this work has been focused on the condition of the mounting medium (Brown 1997; Di Giacomo 2017; Neuhaus et al. 2017). As with the glass containers, what has not received as much widespread attention is the condition of the glass microscope slides themselves. Also like the containers, the deterioration of the glass slides can pose a risk to the preservation of the mounted specimens. Glass alteration of slides has been observed to impact the stability of the mounting medium, and in some cases, the usability of the sample (Fig. 4A).

In general, glass alteration in microscope slides is expected to proceed in a manner similar to other glass and glass-containing items in museum collections. This includes increased opacity or crizzling of the glass, as well the development of secondary precipitates as either solids or liquid droplets on the glass surface (Fig. 4A–D). The microclimate of the storage drawer or box, as well as the temperature and RH of the storage space, may influence alteration rates and the appearance of alteration-related phenomena (Kaczkowski et al. 2017; Koob et al. 2018). Additionally, the thin glass used in creating microscope slides and cover glass, and the way these items are used by researchers, may be reasonably expected to result in mechanical damage such as chips or breaks (Fig. 4E, F).

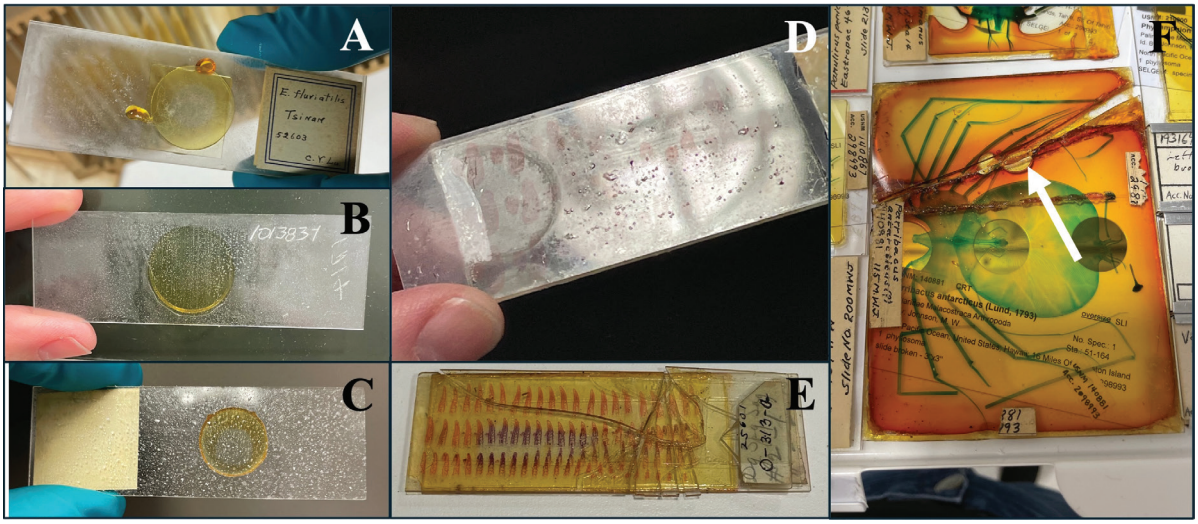

Figure 4. Images of microscope slides with a range of visible deterioration: **A, B** slides with increased opacity (USNM 52603 and USNM 1013837), **C** slide with solid deposits partially obscuring the area of the slide containing the mounted specimen (USNM 52063), **D** slide with liquid droplets due to secondary precipitate deliquescence (USNM 40108), **E, F** slides with significant breaks, impacting the readability of the specimen (USNM 25601 and USNM 140881).

Microscope slides have been created and stored in natural history collections for centuries, and the composition of the glass that can be used has changed over time (Brown 1997; Neuhaus et al. 2017). Early glass microscope slides are exclusively comprised of polished soda lime glass plates which are susceptible to alteration due to their high alkali content. While soda lime glass microscope slides can still be used today, more stable borosilicate glass is also used in creating modern microscope slides and cover glass (Neuhaus 2017).

Materials and methods

Sampling methodology

Due to the large number of fluid collection jars and microscope slides at NMNH, as well as the complex logistics involved in locating and assessing all of these items, the decision was made to focus this study on the collections housed in the Department of Invertebrate Zoology. This department was chosen because it is one of the oldest and largest of the natural history collections at NMNH and houses a wide range of slide and container types and configurations.

It is reasonable to expect that certain populations of both containers and microscope slides would exhibit different deterioration rates based on factors such as age, use, or composition. While it is often possible to make educated guesses about the relative age or use-history of specific microscope slides or containers, given the immense size of these collections and the long history of researchers and collections managers involved in their use and maintenance, there are no consistent records kept about the storage glass components. Though most specimens have an associated collection date, it is impossible to know if a specimen has been re-housed in a new glass container or re-mounted on a new slide. It is also impossible to determine how a given specimen has been used, or the environmental conditions under which it has been stored in

the past. This project was limited to an assessment of the current condition of the storage glass collections as they exist today. The impossibility of clearly defining sub-populations of interest also limit this study to an overall assessment of the average condition of the glass across the collection.

Even when considering only the storage glass held in Invertebrate Zoology, the immense number of both containers and microscope slides precluded an assessment of the condition of each individual glass item. Instead, a statistical sampling survey of both types of storage glass was undertaken. Due to the differences in presentations of glass alteration expected between glass fluid containers and glass microscope slides, these collections were considered and surveyed separately.

The Cochran formula for a 95% confidence interval and 5% error was used to calculate all sample sizes discussed in this paper, and a random number generator was used to select the items included in all sample sets. In the case of microscope slides, two storage locations were considered and sampled as separate populations, requiring post-stratification weighting. Care was taken to ensure that the sample set was selected from as complete a list as possible of all containers and microscope slides held in Invertebrate Zoology to ensure that the results of this survey represented the overall collection as accurately as possible.

Determining population size

Determining the correct statistical sample size and drawing a representative sample set for both the containers and microscope slides presented some significant challenges. To calculate a sample size for surveying, more information was needed about the number of containers and microscope slides held in the collection. Because the glass itself is not part of the collection, there are no catalog or database records indicating how many containers or microscope slides exist within Invertebrate Zoology. Instead, one catalog number may refer to several hundred specimens all contained in dozens of jars, or inversely, dozens of individually cataloged specimens may be housed together in the same container. Though typically individually mounted, a similar problem exists for microscope slides where dozens of histological slices of the same specimen may be spread over multiple slides.

Jars and vials

The glass containers used in Invertebrate Zoology are all housed on compact storage shelving in six specially designed storage rooms at the Smithsonian's Museum Support Center. Each shelf can hold a large number of individual containers, and counting the jars on each shelf was determined to be unrealistic. Instead, an estimate of the total number of containers was obtained by determining the average number of containers on each shelf across the collection. While the height of each shelf can vary, the footprint of each shelf in the compact storage system is consistent. Each of the 32,775 individual shelves in the six rooms used by Invertebrate Zoology were assigned a unique identifying number, and a sample set of 382 shelves was identified for assessment.

Each of these shelves was located and the number of jars held on each shelf was counted and assigned a unique identifier. A total of 9,878 jars were counted

through this process, averaging 25.2 (± 1.4) jars on each shelf. Based on this data, it is expected that Invertebrate Zoology storage houses approximately 825,000 jars.

It was determined to not be feasible to try and count the number of internal vials held inside each jar counted in this portion of the study, but the number of containers with any quantity of internal vials were recorded. A total of 2,532 counted containers (25.6%) were found to have at least one internal vial.

Microscope slides

The microscope slides held in Invertebrate Zoology are stored in a wide range of configurations, from slide boxes to catalog card cabinets, to modern flat storage collection cabinets. Additionally, the size of the slides themselves varies, resulting in different numbers of slides fitting on any given shelf. This variation meant that it would be difficult to estimate the population of slides based on any larger grouping such as number of boxes or number of shelves. Additionally, within these storage configurations, spaces are often left open between slides of different species to accommodate future collection growth.

As a result of these complications, a full item-level count of all the glass microscope slides held in this collection was undertaken. A total of 444,261 individual microscope slides were counted by hand and assigned unique identifiers based on collection and storage location. A little less than half of the microscope slides in Invertebrate Zoology's collection (164,606) are housed at the Natural History Building in Washington, D.C., including approximately 126,000 slides that are part of the National Parasite Collection. The remaining 279,655 slides are housed at the Smithsonian's Museum Support Center in Suitland, Maryland.

Visual assessment of glass condition

Following the determination of the population sizes for both microscope slides and containers, it was possible to calculate sample sizes for item-level condition assessments. Two independent condition survey questionnaires were developed for both containers and microscope slides to gather data on the structure and format of the glass as well as the presentation of any observed indications of alteration. The scope of this project was limited to recording information about the current observable condition of the surveyed glass as determined through visual inspection alone. No magnification or correlated analytical studies were used. This decision was made to make the project achievable with the available resources and within the pre-determined timeframe as well as to make it possible to replicate this study at other institutions regardless of available equipment.

To ensure replicability of the results, the survey questions were formatted such that the answers available for each question were both exhaustive and mutually exclusive. Additionally, each of the alteration phenomena considered by the survey were tracked independently of one another rather than relying on a pre-determined scale or series of descriptions. To ensure that the criteria used to assess the condition of these items were consistent and replicable, detailed sets of guidelines and rules, referred to as Reference Manuals, were developed to assist the surveyors in filling out the survey forms (Suppl. materials 1, 2). The survey forms for

each of the two surveys were created as digital fillable forms using the software program Alchemer (Alchemer v.2025.07.30.00, Last release 07/30/2025).

Prior to surveying in either collection, a series of formal test studies of the survey forms and Reference Manuals were carried out to ensure the efficacy of the assessment criteria, as well as to attempt to quantify and minimize interobserver variability in the survey results. These studies were carried out on small numbers of randomly selected items (usually ~20). Following each test study, the team met to review the response report and changes were made to improve response consistency. Questions were added, refined, or removed before the forms and instructions were tested again, and this process was repeated until the team felt confident that they had the strongest possible survey.

Fluid filled jars and vials

A random sample of 392 individual jars were selected from the population of 9,878 jars that had been hand-counted during the initial counting survey process. These jars were each located and assessed in situ. Information was gathered about the jars' configuration including the type of closures and the quantity of any contained internal vials. Visual indications of deterioration of the glass were also recorded including any visible increased opacity of the glass or the presence of solid surface deposits. Weeping was not considered in these collections due to the likelihood that any liquid observed was due to the contained fluid rather than glass alteration. Each of these visible indications of alteration were recorded separately for each jar as well as any apparent cracks and breaks in the glass (Fig. 3F) (Suppl. material 2).

It is important to note that distinguishing between dust and debris on the glass surface and solid deposits that are indicative of glass alteration proved challenging as the containers were frequently found to have dust, residues, or possible mold on the exterior surface (Fig. 3H). The surveyors were permitted by the collection managers to wipe the exterior surface of the containers to attempt to distinguish between these two possibilities. In cases where it was truly impossible to determine if a given container was altering or simply dirty, the survey guidelines required the surveyors assessing these items to err on the side of recording the presence of either increased opacity or solid surface deposits. This ensured that all potential instances or glass alteration were captured but also means that the resulting data should be considered an upper limit for the proportion of containers with glass alteration in this collection.

Dried jars

It is difficult to adequately assess the condition of glass in fluid filled containers, as the refractive index of the preservation fluid corrects for some of the light scattering and resulting opacity that is a typical indication of altering glass. Also less noticeable in fluid are the iridescent layers that tend to form on the surfaces of some submerged glass vessels (see Fig. 3G).

While it was not feasible due to time and financial constraints to empty and dry all 392 individually surveyed jars, in order to attempt to understand the

impact of fluid on the assessment of glass condition, 56 of the surveyed jars were selected for secondary assessment. These jars were randomly selected from the list of 392 individually surveyed jars. To minimize risk to both staff and collections, items known to be stored in formaldehyde, and valuable type collections were excluded from this set along with uncatalogued specimens. The specimens in these jars were rehoused, and the jars were rinsed and allowed to dry before being assessed again for any visual indications of altering glass. Visibly degraded jars were set aside for further analysis and not reused.

Microscope slides

To determine if there is any statistically significant difference in the condition of the glass slides housed at the Natural History Building or Museum Support Center, the slides at each location were sampled and surveyed as separate populations. A total of 780 slides (393 at NHB, 387 at MSC) were assessed for glass deterioration including the presence of weeping or solid secondary precipitates, increased opacity, or any chips, cracks and breaks. As with the container survey, each form of visible glass alteration or deterioration was assessed separately based on pre-defined descriptions and definitions (Suppl. material 2).

Similarly to the container survey, reliably distinguishing between increased opacity and surface deposits stemming from altering glass and dust, debris, residual oil, or even residues from likely cigarette smoke on the surface of some of the slides proved challenging. To attempt to distinguish between glass alteration and surface debris, the surveyors assessed each slide before and after cleaning with a dry Kimwipe. Increased opacity that could not be removed in this manner was noted in the survey responses. Distinguishing between solid deposits stemming from alteration and dust or debris was more challenging as both would be expected to wipe off the glass surface. In cases where it was not possible to distinguish between these two possibilities, the survey guidelines required the surveyors to record the presence of solid surface deposits on that slide. As with the container survey, this means that all instances of possible glass alteration were captured, but the results represent an upper limit of glass alteration in this collection.

Information was also gathered by the survey about the size and configuration of each surveyed slide, including the presence of any component materials in addition to the requisite glass, mounting media, and specimen. Data were also gathered about the method of identification used to label each slide and any loss of identifying information due to deterioration.

Results

Jars and vials

Assessment of fluid filled jars

Of the 392 individually surveyed jars, approximately 62.5% (± 4.8%) showed at least one visible indication of potential glass alteration as defined by the survey form's Reference Manual (Suppl. material 1). Over 40% of the surveyed jars

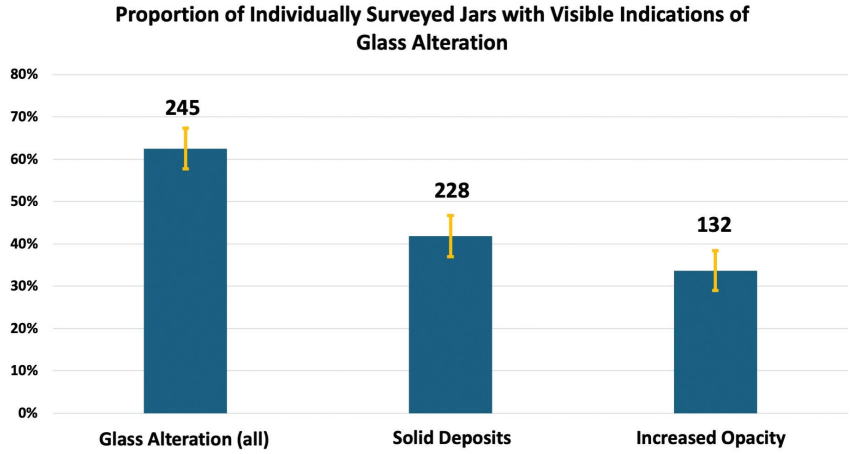

Figure 5. Graph showing the proportions and counts of individually surveyed jars with observed indications of glass alteration on the glass surface. Error bars represent the calculated uncertainty in the results.

had solid secondary precipitate deposits present, while approximately 33% displayed increased opacity or crizzling. Fig. 5 shows the counts and proportions of surveyed containers with these observed indications of glass alteration. None of the jars surveyed were found to have any cracks or breaks.

Information was also collected about the configuration of each surveyed jar. A total of 99 (or 25.2% ± 4.3%) of the surveyed jars were found to contain internal vials. Overall, these jars collectively contained 599 internal vials, resulting in an average of 6.1 ± 0.7 vials in each of the nested jars. However, more significantly, an average was calculated for all of the surveyed jars at ~1.5 internal vials for every jar assessed, indicating that the majority of glass vessels held in this collection are internal vials, not jars. The large number of small-scale specimens held in Invertebrate Zoology likely accounts for this high number of vials and this proportion would be expected to vary based on the collection being considered.

Assessment of dry jars

Due to the difficulties in assessing the condition of glass surfaces that are in direct contact with fluid, 56 jars were randomly selected from the population of individually surveyed jars to be emptied and re-assessed when dry. While these jars did not constitute a large enough sample set to draw rigorous statistical conclusions, some observations were made through this process that do aid in understanding how glass alteration appears in fluid collections.

The most commonly observed difference between jars before and after they were allowed to dry was the presence of an iridescent coating on the internal surface. Of the 56 jars assessed in this manner, 24 were found to have iridescent surfaces on the internal glass face. This feature is nearly impossible to visualize on the internal glass surfaces for fluid-filled containers, so much so that the presence or absence of this surface layer was not recorded in the initial survey of fluid-filled jars. Fig. 6 shows a comparison of how one of these jars appeared with and without fluid contents.

This iridescence was characterized using imaging and compositional mapping with Scanning Electron Microscopy – Energy Dispersive X-Ray Spectroscopy

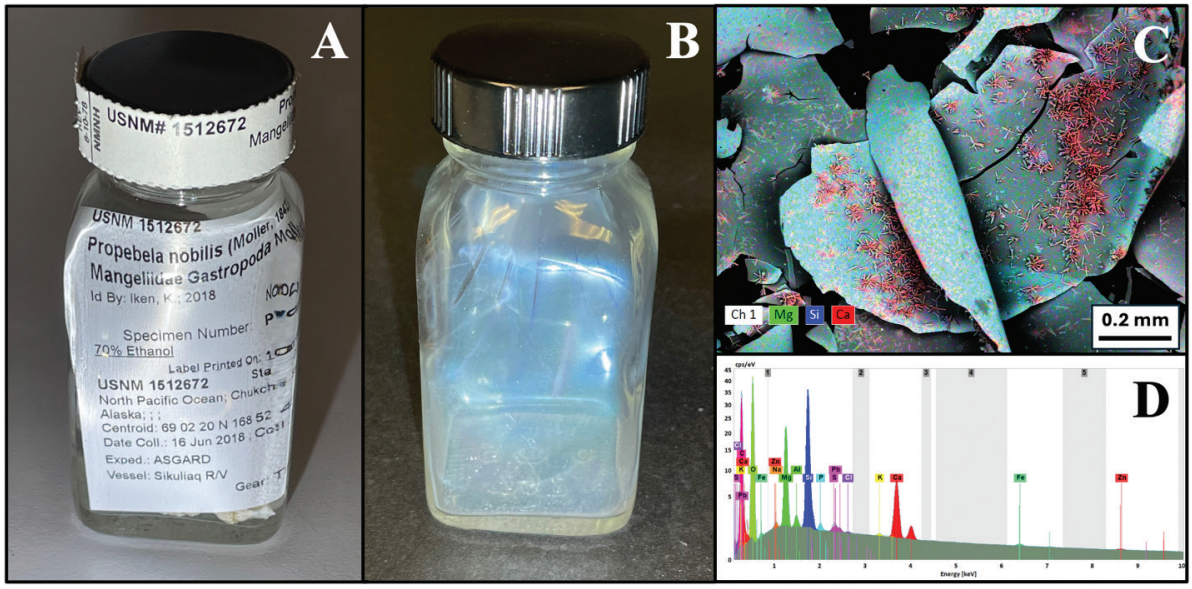

Figure 6. A jar from the collection in Invertebrate Zoology (USNM 1512672) as it was found in the collection space (**A**), the same jar after being emptied and allowed to dry (**B**), SEM-EDS map (Image credit: Thomas Lam) (**C**) and corresponding EDS spectrum (**D**) from delaminated flakes of iridescent material.

(SEM-EDS) of friable samples of this material. This analysis indicated that these iridescent layers are complex silicate products, similar to the archeological weathering layers observed on glass that has aged in a submerged or burial environment (Fig. 6) (Heimann 2017; Gueli et al. 2019; Zanini et al. 2023). These layers and the mechanisms by which they form is an area in need of further study.

The survey results for the dried jars were compared to the results recorded for those same containers while they were fluid-filled. At least one visual indication of glass alteration was noted on 44 (78%) of the containers when assessed dry, compared to 32 (57%) of the containers when assessed wet. Increased opacity was considerably easier to visualize on the surface of dry jars (35 jars or 62%) than when those same jars were surveyed with fluid (19 jars or 33%). As might be expected, however, fewer jars with solid deposits or likely secondary precipitates were observed on the dry jars as compared to the fluid-filled data, since the jars were rinsed prior to drying and assessment, washing away some or all of these surface deposits. More work is needed to understand the impact of the presence of fluid on the ability of collections professionals to accurately assess the condition of fluid storage containers.

Microscope slides

A total of 780 microscope slides were located and assessed as part of this survey. Information was gathered on the condition of the glass components of each surveyed slide. Overall, 34.7% (± 3.5%) were found to have some visual indication of altering glass on at least one of the glass components. Fig. 7 shows the relative rates of each alteration phenomenon observed on the surveyed slides. The most common issue of concern for microscope slides recorded by this survey was the formation of solid surface deposits.

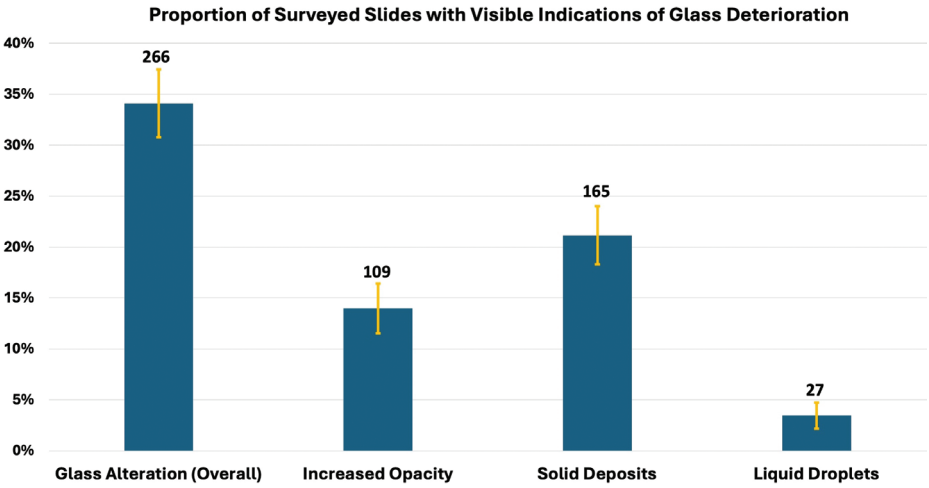

Figure 7. Graph showing the proportions and counts of surveyed microscope slides which were observed to have each recorded visible indication of glass alteration. Error bars represent the calculated uncertainty in the results.

No statistical difference in the proportion of surveyed slides with visible glass alteration was found between the slides housed at the Museum Support Center (36.4% ± 4.8%) and those housed at the Natural History Building (31.8% ± 4.6%). However, some notable trends were found in the alteration rates in smaller collection spaces in both buildings. Most of the collection spaces were found to have solid deposits on between 10–25% of the slides. However, one collection space was found to have solid deposits on 75.3% of the surveyed slides. While this space is located adjacent to a restroom and has known challenging environmental conditions, the survey results cannot identify a specific cause or source for the observed high rates of alteration in this location.

In addition to solid deposits, a small number of slides (27 total) were observed with liquid droplets on the glass surface. These droplets, typically referred to as "weeping" are the result of secondary precipitate products that have deliquesced in a high-humidity environment (Organ 1957). A total of 20 of the 27 slides with weeping were located in a single collection space. Closed slide boxes or cabinets may be functioning as high-humidity microenvironments around these slides, though more work is needed to confirm this as the cause of this observation.

The survey also tracked the presence of cracks, breaks, or chips in the glass slides, which were only observed on a small proportion (5.2% ± 1.5%) of the total surveyed population. Interestingly, most of these observed fractures (65.9%) were found to be in the cover glass, rather than in the support slide. This is likely due to the handling and the relative thinness of typical cover glass (~0.15 mm) in comparison to the thickness of most support slides (~1.2 mm) making them more fragile and prone to breaks.

Mold growth

Reliably identifying the solid deposits on slide surfaces was complicated by the presence of past mold growth on some of the surveyed slides. Fig. 8 shows an example of how these mold colonies appear to the naked eye and under optical microscopy. Mold was identified on 82 (10.5%) of the surveyed slides,

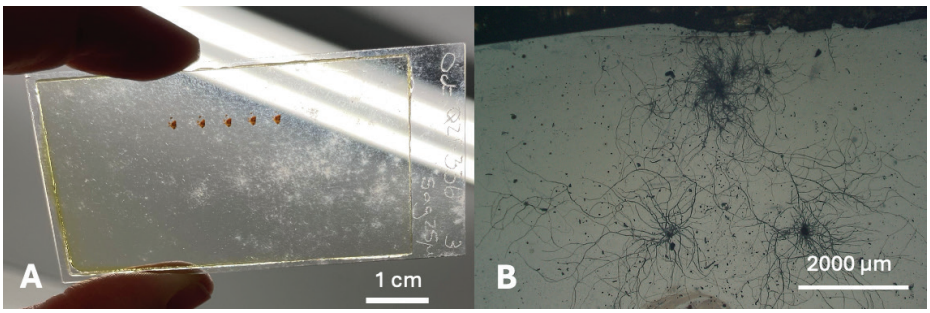

Figure 8. A photograph of microscope slide with visible mold colony growths on the glass surface (Collection ID: Oct Q2 336) and **B** optical micrograph of a mold colony on a glass microscope slide face (Collection ID: Oct NYTd 9).

with almost three quarters of these slides belonging to one collection. As mold growth is unlikely to be correlated with glass composition, these results suggest that some feature of the preparation, use, or storage of the slides in these collections contributed to the growth of mold colonies. While mold growth has been noted in fluid-preserved collections (Dangeon et al. 2020) there is very little information in the literature on mold growth on glass microscope slides. More research is needed to understand how these growths might be impacting the glass surfaces that they are found on.

Storage glass at the Smithsonian

The collection of fluid preserved specimens and microscope slides held by the Department of Invertebrate Zoology serves as a proxy for understanding the likely condition of storage glass across NMNH. While there are some notable differences between the collections and storage methods in Invertebrate Zoology and other departments at NMNH, the results obtained from this survey provide the best available estimates of the prevalence of deteriorating storage glass at the Smithsonian. Based on the results of the survey and the available estimates of the number of jars and microscope slides at NMNH, it would be reasonable to expect that as many as 1.1 million fluid storage jars and 2.1 million microscope slides would show visible indications of altering glass if examined. Obtaining a more complete understanding of the overall impact of glass alteration on these collections is the first step in identifying those at greatest risk and devising protocols and methods for mitigating the impact of glass alteration. While the results of this study provide initial information about the relative frequency of glass deterioration in natural history specimen storage, more work is needed to understand how glass deterioration rates vary by additional factors such as glass age, use, and composition.

Conclusions

Glass makes up an enormous proportion of specimen storage in most major natural history collections, and the alteration and deterioration of this glass is a significant concern for their long-term preservation. This survey serves as a first step in understanding the impact of glass alteration and deterioration on

the preservation of natural history specimens. Glass alteration was observed on 62% of glass jars assessed *in situ*, and this proportion would almost certainly be higher if the containers were emptied and dried prior to evaluation. While a smaller proportion of microscope slides were observed with alteration, the 34% recorded as exhibiting visible glass alteration equates to millions of slides in the overall Smithsonian collections.

The nature of these collections presents some unique challenges to the long-term preservation of this glass and by extension, the specimens they store. The long history of these collections has resulted in a wide range of glass compositions and preparation methods, and the immense numbers of microscope slides and fluid containers often makes regular monitoring of the condition of these items impossible. Additionally, environmental factors in natural history collections can also play a detrimental role. The climates of these storage spaces are frequently not as tightly controlled or monitored as they might be in art or collection object storage spaces and in the case of fluid collections, the specific environmental condition goals often prioritize reducing spark risk over material degradation. Higher humidity conditions can contribute to an increased rate of glass alteration, as well as potentially support the growth of mold and corrosion of metal lids and closures. While the use of borosilicate glass whenever possible is likely to significantly improve the stability of the glass components in these collections, replacing all currently existing soda lime glass slides and containers with borosilicate would be a prohibitively costly and time-consuming endeavor. Understanding how the condition of glass in natural history collections changes over time and how glass alteration and deterioration impact the specimens they contain is essential to the long-term preservation of these collections.

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Additional information

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The authors have declared that no competing interests exist.

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Author contributions

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Data availability

All data that support the findings of this study are available upon request from the corresponding author.

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Supplementary material 1

The Glass Deterioration Working Group fluid storage survey reference manual

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Supplementary material 2

The Glass Deterioration Working Group microscope slide reference manual

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