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## Mineral-specific issues in 3D scanning and printing for digital collections, outreach, and display

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### Abstract

Three-dimensional (3D) scanning and 3D printing of natural history specimens presents interesting opportunities for informal and formal science education, as well as specimen preservation and display. Museum staff in several museums have begun scanning and making specimens available online. However, very few mineral specimens are available as scanned 3D objects, because minerals present unique challenges in scanning. Specifically, their variable surface reflection properties (“luster”) and surface complexities make them complicated specimens to reproduce. This paper examines the variables involved in 3D scanning and 3D printing mineral specimens, lays out criteria for ideal candidates, and presents workarounds to common problems. In general, ideal mineral candidates for 3D scanning and 3D printing are opaque, with no overlapping components that create obscured cavities, have a distinctive form or habit, and have light colour and dull or earthy luster. Non-ideal candidates can still successfully scan and print, though workarounds are often required.

**Keywords:** 3D printing, 3D scanning, digitization, digital objects, mineral collections

### Introduction

Over the last twenty years, science educators and researchers have started experimenting with 3D scanning and 3D printing of museum specimens for digital collections, outreach, and display. The Smithsonian X 3D Archive, launched in 2013, now holds more than 2,500 3D objects that can be downloaded and printed on at-home 3D printers (Smithsonian n.d.). The Digital Archive of Natural History has released dozens of 3D scans of insects (DiNArDa n.d.). The University of Michigan Museum of Paleontology has released collections of 3D fossils, including an entire *Allosaurus fragilis* skeleton (University of Michigan Museum of Paleontology n.d.). The GeoFabLab on Thingiverse provides dozens of fossils, geologic terrains, and a few crystal forms (GeoFabLab n.d.). At this point,

an interested person could 3D print themselves almost an entire natural history museum (though, interestingly, there are very few mineral specimen 3D scans online).

These 3D digital objects have interesting applications in geoscience pedagogy, both formal and informal, especially in the wake of the 2020 COVID lockdowns that kept large numbers of students away from lab specimens and field trips. SketchFab collections like those of Sara Carena offer free digital collections of geologic terrains, rocks, and fossils. Horowitz and Schultz (2014) use 3D topographic maps in the classroom, Cases and Estop (2015) integrate 3D printed crystal forms into a crystallography class, and Savoian and Holt



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(2017) use it to 3D print large-scale pollen models to teach about morphologies. Rocks and geologic specimens can also be 3D printed for classroom instruction (as explored in Squelch 2017, Ishutov *et al.*, 2018, and Hasiuk 2014). Hands-on materials are particularly helpful for students with vision differences (e.g., Travis 1990, Asher 2001, Permenter and Runyon 2003, Ceylan 2011). Additionally, 3D replicas can be used by exhibition designers to design mounts for display, reducing the risk of breaking fragile specimens.

However, in all these applications, 3D scanning and 3D printing of *mineral* specimens has not been explored, and very few digital 3D models of mineral specimens are available online. This is likely because mineral specimens present unique challenges for 3D scanning and 3D printing: their range of surface reflective properties (“luster”), changes in opacities, and surface complexities can make them challenging candidates for 3D scanning.

This paper examines the variables that affect 3D scanning and 3D printing of minerals, with the goal of presenting workarounds to common issues and laying out guidelines for ideal mineral candidates for 3D scanning and 3D printing. This paper is aimed at small-scale 3D scanning and 3D printing projects, appropriate for a university or museum mineral collection.

## Methods

### Technology

Three dimensional (3D) scanners have a wide range of capacities; Cieslik and Harris (2020) give an excellent overview of 3D scanning technology options for natural history collection digitization projects.

The project outlined in this article used a scanner with a budget and technical capacities manageable by a university: a Shining3D EinScan-SP, part of the Bryn Mawr College Makerspace. This is a structured light scanner: it projects a series of light-and-dark stripes onto the specimen (unlike a laser scanner, which projects a laser beam). Two cameras on either side of the projector then use triangulation to calculate the distance between themselves and each point the light touches. The scanner’s software uses those triangulations to build a topographic map of the specimen. As the stage upon which the specimen sits is rotated, the object is scanned again, and a 3D topographic map of the object is built.

A desktop 3D scanner is appropriate for most specimens in a typical university collection. Unlike

a laser 3D scanner, structured light scanners can also map surface texture, which allows the 3D objects to carry their original colours and patterns. The size requirements are appropriate for all but our largest and smallest minerals: 30 × 30 mm to 1200 × 1200 × 1200 mm. Most of the specimens in the Bryn Mawr Mineral Collection are between 40 × 40 × 40 mm and 1000 × 1000 × 1000 mm: the size you would hold in your hand (a “hand sample”). This is a common size range for mineral collections, because “hand sample” is a common geologic sampling size.

Before use, the scanner was calibrated using a dot calibration panel, and white balanced using white paper. For projects that require high fidelity colour, white balancing should be done using a photographic colour balance chart and a scanner built specifically for high-fidelity color scanning (ideally, higher 2D resolution than the 1.3Mpx Einscan used here). Minerals were scanned, then repositioned so any surfaces hidden in previous scans could be seen, and scanned again. This was repeated until each surface was scanned. Afterwards, watertight digital mesh models were constructed using the EXScan software. These watertight models interpolate to fill in gaps in the digital 3D structure so it can be printed on a 3D printer.

Watertight digital 3D models were then transferred to Ultimaker Cura software, where they were converted to 3D printable files. These were uploaded to an Ultimaker S5 Pro 3D printer in the Bryn Mawr Makerspace, and printed using Ultimaker PLA (polylactic acid) extruded material with water-soluble Ultimaker PVA (polyvinyl alcohol) as support material. PLA was chosen because it is commonly used in small-scale 3D printers, and one of the goals of this project was to produce 3D objects that could be printed at home by amateurs. However, in selecting materials for 3D prints, care should be taken to choose materials appropriate to the purpose of the project. For example, because PLA is a bioplastic derived from corn starch and sugar cane, it degrades when exposed to prolonged humidity. This makes it a more environmentally-friendly choice than other thermoplastics, but a poor choice for long-term use in a museum context. Care should also be taken in storing these materials; Stefaniak *et al.* (2018) demonstrated that 3D printed materials using PLA and ABS can off-gas styrene, a known carcinogen. In particular, acidic off-gassing could impact pyrite oxidation (see Larkin 2011 for a deeper discussion on pyrite preservation). Cimino *et al.* (2018) also review safety considerations in 3D printed materials in contact with art work.

For most specimens, the thickness of the 3D printed walls was set to 1 mm; specimens with fragile protruding components were set to 3 mm. After 3D printing, the 3D prints were soaked in water baths to dissolve the support material. It should be noted that any 3D printed material stored with specimens must pass accelerated aging tests (e.g., Oddy tests, Oddy 1973), to ensure that it does not emit gasses that could damage specimens.

#### *Sample selection*

The Bryn Mawr Mineral Collection is ideal for exploring the variables in mineral 3D scanning and 3D printing because of its breadth of specimens: the collection holds more than 40,000 minerals. This means there are dozens of specimens that fit the criteria of (for example) submetallic luster, dark colour, high surface complexity, interesting crystal form, etc.

All specimens reported here are from the Bryn Mawr Mineral Collection. Most are from the George Vaux Jr. Collection, assembled by Philadelphia naturalist George Vaux Jr. (1863 - 1927) from the mid-1800s to early-1900s, and donated to Bryn Mawr by his heirs in 1958. Specimens from this collection are labeled in the format V0000, where V indicates Vaux. This work also uses minerals from the Theodore Rand Collection, assembled by Philadelphia mineralogist Theodore Rand (1836 - 1903) in the mid- to late-1800s, and donated to Bryn Mawr by his heir in 1903; these are designated Rand, then a number. Finally, a few specimens from the Arndt Acquisitions are included, with the label AA and the number.

Specimens were selected with the goal of assessing the range of capabilities for the 3D scanning and 3D printing process. The variables considered were: colour, luster, habit, and surface complexity. Structured light 3D scanning is incompatible with anything other than opaque objects; however, some translucent or transparent minerals were included to test whether applying opaque materials to their outer surfaces could make them scannable. Size was not considered; all specimens were typical “hand sample” sizes.

Within the category of luster, minerals were selected to represent the most common surface lusters. “Adamantine” lusters refer to minerals that sparkle as a diamond would. “Waxy” minerals look like their surfaces are covered in wax (the microcrystalline quartz chalcedony often has this distinctive look). “Greasy” minerals look like they have a thin film of grease over the surface (large

halite crystals often have this). “Vitreous” minerals look like they are made of glass, though this can be coloured or opaque glass. “Resinous” minerals look like amber or resin (sphalerite is the famous example of this). “Metallic” lusters look like polished metal (many pyrites), and “submetallic” look like unpolished metal (some hematite). “Pearly” lusters are nearly iridescent, like the inside of an oyster or a pearl (some talc). “Silky” lusters are often accumulations of fibrous or acicular mineral forms, creating a satin-like texture (some forms of gypsum do this). “Dull” luster looks dull. “Earthy” luster looks like compressed dirt. Taken together, these lusters represent the vast majority of minerals in a typical collection.

#### **Results**

Scan results are tabulated below by luster and surface complexity. Surface complexity exhibited some control on how easily minerals scanned: high-complexity surfaces were more difficult to scan (Table 1). Similarly, the combination of colour and shine was important: the easiest minerals to scan were dull; the hardest to scan were dark and shiny (Table 1).

“Shiny,” though, was a more complex variable than “shiny” vs. “dull.” Some “shiny” lusters scanned easily (e.g., metallic, submetallic, pearly, silky), while others did not (e.g., adamantine, waxy, greasy, vitreous; Table 2).

#### **Time requirements**

Each full-resolution scan scan (of full-turns, at 32 steps) required about 15 minutes; however, most specimens required more than one scan. Specimens with dull lusters required the fewest scans; shinier specimens required more. The dull Sandy Topaz BMC-V5847, for example, required only one scan; the shiny Garnet BMC-V5488 required five.

After each scan, approximately 5 minutes of additional editing/optimization was required for simple specimens. More was required for specimens that had abnormalities in their scans. For example, the Native Silver BMC-V0455 moved slightly during one scan, producing a second tendril of silver; this had to be edited out.

After editing, each specimen required an additional 5-10 minutes to convert to a watertight mesh object.

In all, then, each specimen required somewhere between 25 and 100 minutes to produce a digital 3D object.

Table 1. Tone and shine vs. surface complexity.  
 (S) indicates a mineral was successfully scanned  
 (F) indicates a mineral that failed to be scanned, even with workarounds summarized in the Conclusions section  
 \* indicates a mineral that failed to scan naturally, but scanned successfully once cornstarch was applied  
 – indicates a mineral that failed to scan naturally, and failed to scan with cornstarch

	High Complexity	Medium Complexity	Low Complexity
<b>Success:</b>	<b>63%</b>	<b>93%</b>	<b>94%</b>
<b>Light &amp; Shiny - 67% success rate</b>	<b>Wulfenite BMC-V8722 (F)</b> <b>Zeolite BMC-V6329 (F)</b> <b>Mica BMC-V6788 (F)</b>  Selenite BMC-V8443 (S) Calcite Stalactite BMC-V3489 (S) Mimetite AA343 (S)	<b>Wavellite BMC-V7827(F)</b>  Copper BMC-V543 (S) Emeralds BMC-V5096 (S) Rand Calcite Pearls (S)	<b>Quartz BMC-V2276 (F<sup>-</sup>)</b>  Microcline BMC-V4644 (S) Quartz BMC-V2502 (S) Pyrite BMC-V1110 (S) Wavellite BMC-V7841 (S)
<b>Dark &amp; Shiny 55% success rate</b>	<b>Pyroxene BMC-V4888 (F)</b> <b>Galena BMC-V0769 (F)</b>  Hematite Rose BMC-V2096 (S)	<b>Goethite BMC-V3198 (F*)</b> <b>Sphalerite BMC-V0846 (F)</b>  Stibnite BMC-V0641 (S) Staurolite BMC-V6943 (S)	<b>Cassiterite BMC-A244 (F)</b>  Hauerite BMC-V1298 (S) Garnet and Mica BMC-V5486 (S) Wurtzite BMC-V0958 (S)
<b>Light &amp; Dull - 93% success rate</b>	<b>Wulfenite BMC-V8702 (F)</b>  Quartz ps Calcite BMC-V2730 (S) Wurtzite BMC-V0958 - dull component (S) Bayldonite BMC-V7810 (S)	Stilbite BMC-V6541 (S) Quartz ps. Anhy. BMC-V2719 (S) Aragonite Rose BMC-V4055 (S) Zeolite BMC-V6662 (S)	Rhodonite (S) Topaz BMC-V5847(S) Malachite ps. Cuprite BMC-V1942 (S) Leucite BMC-V4792 (S) Quartz ps. anhydrite BMC-V2719 (S) Kaolinite ps. Feldspar BMC-V4596 (S)
<b>Dark &amp; Dull 100% success rate</b>	Native Silver BMC-V0455 (S) Native Silver BMC-V0439 (S) Goethite BMC-V3199 (S)	Ilvaite BMC-V6074 (S) Conicalcite BMC-V7801 (S) Native Copper BMC-V5047 (S)	Staurolite BMC-V6344 (S) Vivianite BMC-V7724 (S) Lava Stalactite BMC-V4820 (S)

Time requirements for 3D printing varied by the size of the objects. Native Copper BMC-V0543 measured about 2 x 1 inches, and required about 2.5 hours to print. Goethite measured 3.5 x 4.5 inches and required 22 hours to print. These time estimates change as a function of wall thickness as well.

### Discussion

The aims of this project were to analyze the variables that affect 3D scanning and 3D printing of mineral specimens, to develop ideal specimen criteria for structured light scanning, and to establish work-arounds for non-ideal mineral specimens.

Mineral opacity is most important of the variables involved; transparent materials do not scan with structured light scanners. The opacity issue means even minerals with very faint translucency often fail to scan. Even minerals with slightly translucent components fail to scan those areas. For example, the Quartz after Calcite BMC-V2276 reported here had a section of slightly transparent crystals at its base; these failed to scan, regardless of lighting conditions (Figure 1). The digital 3D mesh modeling was able to interpolate over the missing sections, so the scan was still successful, but only because the areas in question were on the bottom of the specimen. Zeolite BMC-V6329 was judged opaque upon visual inspection (Figure 2A), but was completely invisible to the scanner. Workarounds to opacity are discussed at the end of this article.

Table 2. Lustres

\* indicates a specimen that failed to scan naturally, but successfully scanned once cornstarch was applied.  
 – indicates a mineral that failed to scan naturally, and failed to scan with cornstarch.

Luster	Success	Successful Scan	Failed Scan
<b>Adamantine</b>	0%		Wulfenite BMC-V8722 Titanite BMC-V7033 - adamantine parts Vivianite BMC-V7724 - adamantine face Mica BMC-V6788 - adamantine faces
<b>Waxy</b>	33%	<b>Wavellite BMC-V7840</b>	Goethite* V3198 Cassiterite A244
<b>Greasy</b>	50%	<b>Calcite Stalactite BMC-V3489</b> <b>Mimetite BMC-AA343</b>	Wavellite BMC-V7827 Zeolite BMC-V6329
<b>Vitreous</b>	50%	<b>Garnet component on BMC-V5486</b> <b>Microcline BMC-V4644</b>	Quartz <sup>-</sup> BMC-V2276 Pyroxene BMC-V4888
<b>Resinous</b>	67%	<b>Emerald BMC-V5096</b> <b>Titanite BMC-V7033 - the resinous parts</b>	Sphalerite BMC-V0846
<b>Metallic</b>	80%	<b>Hauerite BMC-V1298</b> <b>Stibnite BMC-V0641</b> <b>Pyrite BMC-V1110</b> <b>Hematite Rose BMC-V2096</b>	Galena BMC-V0769
<b>Submetallic</b>	100%	<b>Native Copper BMC-V0543</b> <b>Native Silver BMC-V0439</b> <b>Ilvaite BMC-V6074</b> <b>Wurtzite BMC-V0958</b> <b>Native Copper BMC-V5047</b>	
<b>Pearly</b>	100%	<b>Mica component on BMC-V5486</b> <b>BMC-Rand Calcite Pearls</b> <b>Quartz BMC-V2502</b> <b>Staurolite BMC-V6943</b>	
<b>Silky</b>	100%	<b>Selenite BMC-V8443</b> <b>Zeolite BMC-V6662</b> <b>Wavellite BMC-V7841</b>	
<b>Dull</b>	100%	<b>Native Silver BMC-V0455</b> <b>Malachite after Cuprite BMC-V1942</b> <b>Quartz after Anhydrite BMC-V2719</b> <b>Quartz after Calcite BMC-V2730</b> <b>Leucite BMC-V4792</b> <b>Sandy Topaz BMC-V5847</b> <b>Vivianite BMC-V7724 - the dull faces</b> <b>Staurolite BMC-V6344</b> <b>Stilbite BMC-V6541</b> <b>Wurtzite BMC-V0958 - dull component</b>	
<b>Earthy</b>	100%	<b>Aragonite Rose BMC-V4055</b> <b>Conicalcite BMC-V7801</b> <b>Goethite BMC-V3199</b> <b>Bayldonite BMC-V7810</b> <b>Kaolinite ps. Feldspar BMC-V4596</b> <b>Native Copper BMC-V5047 - earthy parts</b> <b>Lava Stalactite BMC-V4820</b>	

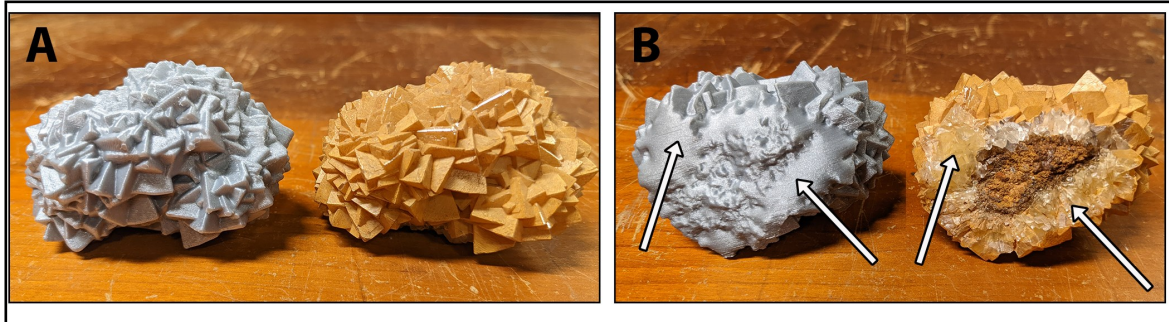


Figure 1. Quartz after Calcite BMC-V2276. A) 3D print of specimen (left) vs. actual specimen (right). The scanner and printer have reproduced the complex crystal surface well. B) Bottom of specimen. Arrows point to areas of translucence on the original specimen, which the scanner has failed to reproduce. The mesh-making software interpolated across those areas, producing smoothed zones.

The second most important variable was surface complexity: only about 63% of the minerals examined here with high surface complexity successfully scanned. The biggest issue was overhang. The Wulfenite BMC-V8702 specimen, for example, failed to scan because its two overlapping tablet-shaped crystals produced an internal cavity invisible to the scanner (Figure 2B). The BMC-V8443 Selenite specimen had several cavities where knots of fibers curled over themselves; these also failed to scan, although the mesh modeling's interpolation produced a passable 3D object, even though some detail was lost.

Mineral luster was also important in determining whether a mineral scanned, though this is a more complex variable. Dull and earthy minerals scanned consistently well; though these rarely present crystal forms that are interesting as 3D objects.

Minerals with some degree of “shine” were more complicated: In general, minerals with high shine did not scan well. For example, the adamantine

Wulfenite BMC-V8722 failed to scan, as did the adamantine surfaces on Vivanite BMC-V7724, Titanite BMC-V7033, and Mica BMC-V6788 (Figure 2C). Specifically, the components that failed to scan were the highly-reflective crystal faces. Presumably, this is because the highly-reflective faces saturate the scanner's receptors. To a certain extent, this can be compensated for by reducing the lighting on the specimen. For example, the shiny vitreous garnet in BMC-V5486 eventually scanned at a lower light setting (see Workarounds section below); however, for dark and shiny minerals, this renders them invisible. This is why dark and shiny minerals had the lowest rate of success in scanning.

For other specimens, however, their shininess was a more nuanced variable. For example, Goethite BMC-V3198 and Stibnite BMC-V0641 are both gunmetal-gray specimens, both shiny, and both have medium surface complexity (the Goethite has smooth botryoidal curves that divot into crevices, while the Stibnite has long, often deep grooves

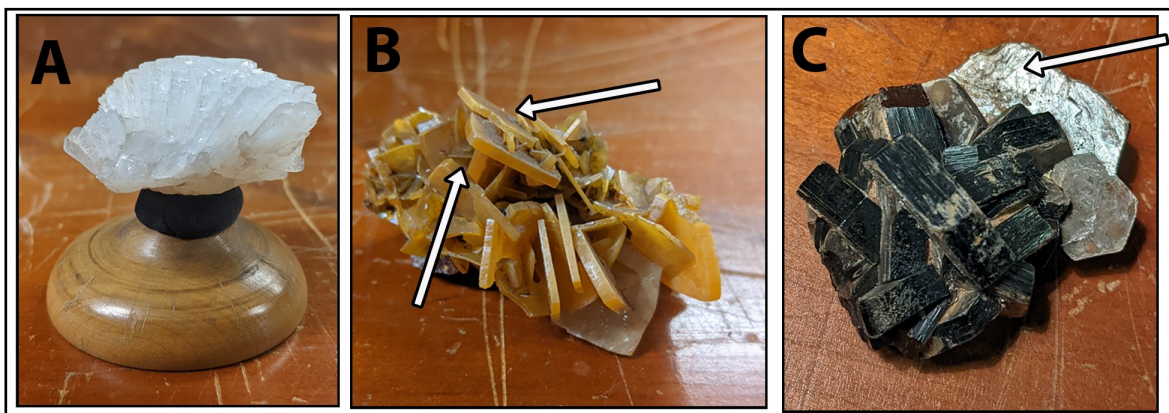


Figure 2. Failures. A) Zeolite BMC-V6329 appeared opaque, but was translucent enough to be invisible to the scanner. B) Wulfenite BMC-V8702 had two overlapping crystals (arrows) that created a hidden space inside. This was invisible to the scanner and could not be duplicated. C) Mica BMC-V6788 had high-shine cleavage planes (arrow) that were invisible to the scanner.

running its length). Yet the Goethite failed to scan without cornstarch application (see Workarounds below), and the Stibnite succeeded. It is possible this was due to differences in their specific shininess (Goethite was waxy, Stibnite metallic), or a function of both shine and morphology (Figure 3).

In general, greasy, waxy, and vitreous minerals were problematic to scan, though other shiny lusters were usually successful (e.g., silky, pearly, and metallic). It is possible that greasy and waxy minerals also often accompany convex morphologies that scatter higher percentages of light away from the scanner than flat crystal faces. For vitreous minerals, it is possible their difficulty in scanning could arise from lingering translucency, even if they appear opaque in hand sample.

#### Alternative technologies

This project used a structured light scanner that is within the budget and space constraints of a university collection; however, it is likely that a laser scanner would react similarly to the surfaces reported here. Laser scanners, though, might have more trouble with high-scatter surfaces (for example, minerals with complex topographies), and abrupt changes in surface topographies (Cieslik and Harris 2020, p. 16). Both high-scatter surfaces and abrupt surface topography changes are common in mineral specimens. Still, a future comparison between structured light and laser scanners would be useful.

#### Conclusions

Below, we outline the characteristics of an ideal mineral specimen for structured light 3D scanning 3D and printing, and workarounds for non-ideal candidates.

#### *Ideal properties for 3D scanning and 3D printing*

- **Opaque.** Transparent or translucent specimens are inappropriate for reflective scanning. They are invisible to the scanner. *Possible workarounds:* cornstarch application described below. Minerals that are only faintly translucent (e.g., BMC-V4088 Aragonite reported here) might still scan if given very high illumination during scanning.
- **No overhangs.** If a specimen has overlapping surfaces, the scanner will find it very difficult to scan. Wulfenite BMC-V8702 reported here was unable to be scanned because two of the large crystals pointed toward each other, creating a hidden internal space that the scanner could not access. Aragonite BMC-V4083 reported here had multiple overlapping tendrils. The scanner was able to accommodate enough of them that the scan could still produce a successful replica; however, the details of areas between the tendrils were lost.
- **A distinctive form or habit.** For specimens bound for 3D printing, the core property being replicated is form. For example: the Sand Topaz

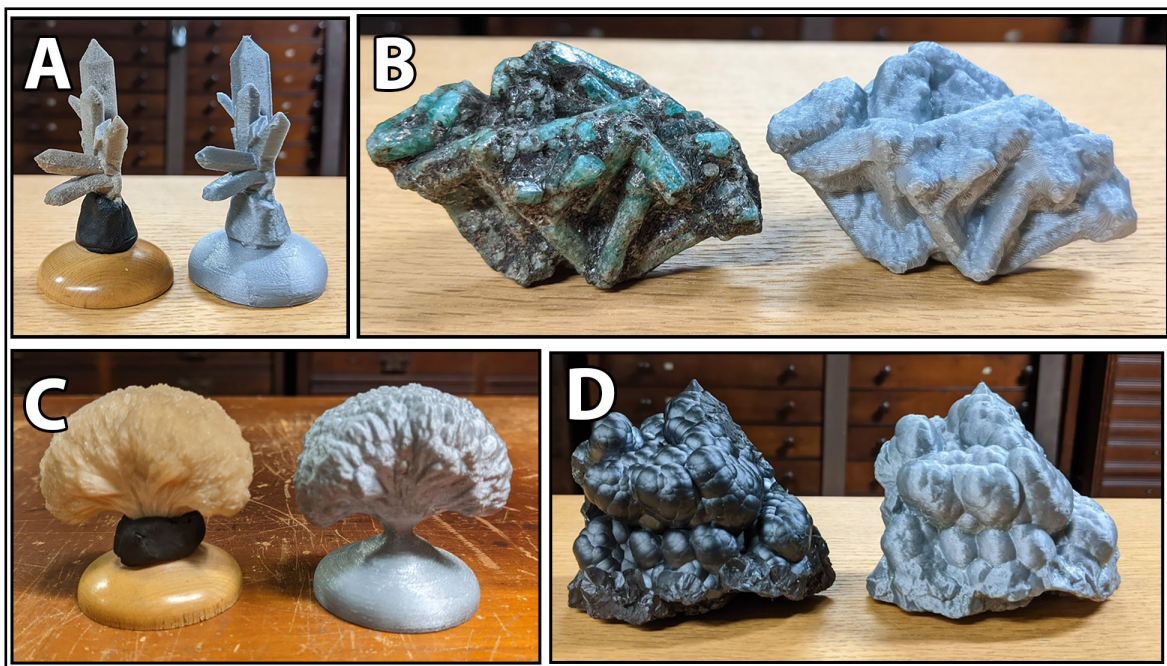


Figure 3. Successful reproductions. A) Sand Topaz BMC-V5847, B) Emeralds BMC-V5096, C) Stilbite BMC-V6541, D) Goethite BMC-V3198.



BMC-V5847 reported here was successful because it had a distinctive crystal form, independent of its colouration. (Figure 3A). Poor candidates would be ones whose most obvious characteristics are in colouring (e.g., banded agate) or a mineral in massive habit, though these might still produce interesting 3D objects that could be viewed digitally.

- **Topographic prominence.** For 3D printing, ideally, a specimen stands up above its surroundings. For example: the Sand Topaz BMC-V5847 reported here was a single prism of crystal, with several smaller prisms radiating away from its base. Poor candidates have all the details collapsed onto a single surface. For example: the Emeralds BMC-V5096 reported here were visually confusing once 3D printed, because the overlapping columns were all on the same plane (Figure 3B). The result was a lumpy-looking rock-shaped object that lacked distinctive crystal form. Similarly, the Wavellite BMC-V7841 reported here had radiating fibers. Although the scanner showed that level of detail, they were all collapsed onto a single surface and less interesting as a 3D form. Flat specimens might still produce interesting 3D digital objects, just not for 3D printing.
- **Light colour.** Structured 3D scanners pick up light colours more easily, though dark coloured minerals can be scanned as long as they have a duller luster. If a specimen has both light- and dark-coloured components, multiple scans at different illuminations are required. *Possible work-around:* multiple scans at higher illumination, and/or cornstarch (see below). For dark minerals with shiny luster, multiple scans can work, but it is time-consuming; the Hematite Rose (BMC-V2096) required 21 scans.
- **Not shiny luster.** Dull or earthy lusters are ideal for structured light 3D scanning; all our dull/earthy specimens were successfully scanned. The scanner was more inconsistent with shiny specimens. In general, the duller the luster, the better.
- **Not bendable or morphable.** This is unlikely to be a common problem with minerals; however, specimens should not change shape during scanning. For example, the Native Silver BMC-V0455 reported here had a long tendril extending beyond its main form. During one scan, the tendril moved slightly relative to the rest of the specimen; in that scan, it appeared as a *second* tendril and required manual editing of

the 3D object to fix. Additionally, the Stibnite BMC-V0641 reported here is attached to a wooden stand by a piece of putty. During one scan, the putty deformed a little, causing the angle between the crystal and the stand to change slightly; this scan had to be deleted and re-done.

- **A size appropriate to the scanner.** The EinScan used here lists its minimum specimen size as 30x30x30 mm, though the smallest specimen successfully scanned here was 15x15x15 mm.

#### **Workarounds for non-ideal candidates**

Despite the limitations, most of the minerals tested for scanning here did successfully scan – eventually, but several required work-arounds:

- **Adjusting the angles:** Multiple scans at varying angles was helpful for many specimens, especially those with overly shiny lusters and complex surface geometries.
- **Opacity:** For translucent or transparent minerals, applying cornstarch or a similar spray-whitener to the surface can produce a scan (see discussion below). For only slightly-translucent minerals, setting the scanner to high illumination can also produce workable results (for example, BMC-V4088 Aragonite reported here). If the specimen is easy to clean without damaging it, a light sheen of cornstarch can be applied to reduce shininess (this does affect the 3D object, which no longer reproduces the specimen's texture). Ideal candidates for this would be sturdy enough to be cleaned afterward, without fine detail that could get gummed up or damaged by the cornstarch. For some specimens, the cornstarch has trouble adhering to the surface, e.g., the Quartz BMC-V2276 specimen reported here, whose scan failed even with cornstarch. It is recommended the cornstarch be applied using an air-puffer or flour sifter, which precipitates a fine-grained, even "snow" of cornstarch onto the specimen. This is preferable to "painting" the cornstarch on with a paintbrush or shaking unsieved cornstarch onto it, both of which result in uneven distributions. Cornstarch can be removed with a paintbrush, sponge, or (if the specimen is exceedingly sturdy) washing it off with water. It is important to completely remove all cornstarch from specimens, because it could attract pests. Also, water should never be applied to specimens that may contain pyrite.

- **Overhangs:** It can help to perform multiple scans at a variety of angles; however, even with systematic repositioning, some overlapping surfaces are too complex for a desktop scanner.
- **Dark colour:** For dark-coloured minerals, increasing the brightness of the illumination can help. For specimens with both dark and light components, a scan at high-lighting can catch the dark materials, followed by a scan at lower lighting for the light minerals.
- **Shiny luster:** Shiny specimens can be scanned by lowering the illumination and/or performing multiple scans at a variety of angles (to change the surfaces producing strong reflections). The resinous emeralds reported here, for example, required five scans to successfully complete (compared to dull minerals, which typically required only 2 scans).

However, for specimens that are both dark in colour *and* shiny in luster, lowering the illumination to prevent shininess has the effect of making the dark-coloured mineral invisible. Hematite Rose BMC-V2096 reported here required 21 scans of various brightnesses and at different angles to capture *most* of the metallic luster of the tablet-shaped plates (compared to 1 or 2 scans for light-coloured, dull-lustered minerals).

- **Cornstarch:** If the specimen is easy to clean without damaging it, a light sheen of cornstarch can be applied to reduce shininess (this does affect the 3D object, which no longer reproduces the specimen's texture). Ideal candidates for this would be sturdy enough to be cleaned afterward, without fine detail that could get gummed up or damaged by the cornstarch. For some specimens, the cornstarch has trouble adhering to the surface, e.g., the Quartz BMC-V2276 specimen reported here, whose scan failed even with cornstarch.  
It is recommended the cornstarch be applied using a flour sifter, which precipitates a fine-grained, even "snow" of cornstarch onto the specimen. This is preferable to "painting" the cornstarch on with a paintbrush or shaking unsieved cornstarch onto it, both of which result in uneven distributions. Cornstarch can be removed with a paintbrush, sponge, or (if the specimen is exceedingly sturdy) washing it off with water. (Cornstarch must be completely removed to avoid pests, and water should never be applied to a specimen that might contain pyrite, as this could initiate pyrite oxidation; Larkin 2011).

- **Scanning fragile or small minerals:** Because the scanner cannot see translucent materials, and struggles with very dark materials, it is easy to prop small or fragile specimens on glass or dark holders. The holders aren't scanned, and the specimens can be more delicately placed.
- **3D Printing fragile specimens:** specimens with fragile, thin extruding components can be reinforced by thickening the walls of the 3D print. For example, Native Silver BMC-V0455 reported here has two long, fragile tendrils protruding from the specimen. Increasing the thickness of the 3D print walls from 1 to 3 mm strengthened it considerably; however, in the initial 3D print, one of the tendrils still snapped off.

#### Mineral species that meet criteria for successful scanning

Though the properties described above rule out a percentage of mineral specimens, there are several mineral groups that frequently have the properties needed for a successful scan.

- **Native Element class minerals (like Gold, Silver, or Copper)** often present interesting mineral forms, opaque surfaces, and lusters needed for successful scans, though exceptionally metallic lusters might require a higher numbers of scans. Dendritic forms can be particularly interesting as 3D digital or 3D printed objects.
- **Oxide class minerals (like Hematite, Goethite, or Magnetite)** are similarly well-suited for scanning. Botryoidal and octahedral habits, for example, are visually interesting and often replicable.
- **Clay group minerals (like Kaolinite)** are ideal candidates for 3D scanning, except for their unfortunate tendency to be boring: they tend to massive habits that do not inspire form replication. However, when clays pseudomorphs into more interesting forms, they can make excellent candidates for 3D scanning. For example, kaolinised Orthoclase crystals make for easy scans and interesting forms (e.g., Kaolinite ps. Feldspar BMC-V4596 reported here).
- **Zeolite group minerals (like Stilbite)** often have light colour, dull luster, and interesting radiating habits.
- **Staurolite and Rhodonite** often have luster and form conducive for 3D scanning and 3D printing.

- **Pseudomorphed minerals** in general are often good candidates: a high percentage of the minerals successfully scanned here are pseudomorphs. Presumably this is because high-shine lusters are not preserved under conditions where mineral replacement is occurring.

Unfortunately, a large percentage of the most common minerals are more difficult – or impossible – to scan: quartz and calcite, for example, are usually transparent or translucent enough to be invisible to a scanner (though there are opaque exceptions). The feldspars, olivine, and the pyroxenes rarely present forms interesting in 3D replication. Amphiboles and micas are often too dark and shiny.

The core conclusion from this project is that only a subset of mineral specimens are appropriate for 3D scanning and 3D printing using technology currently available at the university level. However, that subset is not zero, and the specimens that are appropriate for 3D scanning and 3D printing can produce exciting results. Additionally, many specimens that are not ideal candidates can still be scanned if time is available to devote to the process.

Future work could involve comparisons of different types of 3D scanners. For example, photogrammetry might be a more effective way of building digital 3D models of transparent minerals, as the photographer could control the component 2D images. Additionally, although laser scanners are expected to have similar limitations to structured light scanners, a comparison would be interesting.

One additional issue arising from this work is replication of surface complexity. Many specimens showed a loss of detail, probably during the 3D printing process. Further exploration of detail replication would be interesting, perhaps by systematically varying 3D printing settings, materials, or 3D printer types.

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