3D Model Creation and Processing of Tsuzuraozaki Lakebed Site Pottery

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Introduction

Tsuzuraozaki is a submerged lakebed archaeological site in the northern end of Lake Biwa in Nagahama City, Shiga Prefecture. The site ranges from approximately 10 to 700m offshore and resides at a depth of approximately 10 to 70m underwater. It was originally identified 100 years ago in 1924 as a result of locals pulling up pottery in their nets when fishing in the area. Pottery from the site dates from the Kofun period, approximately 1500 years ago to the Initial Jomon period, approximately 7000 years ago. Investigations using robotic submersibles have identified additional pieces of pottery in the area resting on the lakebed (Yano 2019). Researchers are not sure why so much pottery from such a long duration of time has accumulated in the area. Some suggestions for the pottery presence in the area have been that they were ritually deposited in the area; the result of possible accidents where boats have spilled goods overboard; or that the pottery were dislodged from locations on land and deposited into the nearby lake area due to one or possibly more landslides (Oe 1966, Oe 1975, Maruyama 1986, Ogasawara 1989, Akita 1997). Many of the pieces recovered from underwater have been fairly intact which casts some doubt on the landslide theory, but recent work documenting and investigating pottery from the site might yield some clues as to the circumstances surrounding these pottery pieces, some of which have been likely submerged for thousands of years.

Professor Yano Kenichi from Ritsumeikan University has been involved in several investigations surrounding the Tsuzuraozaki site (Yano 2015, 2019, 2023). In 2022 a new project aimed at recording and documenting the pottery from the site was started. In addition to the broad time span of pottery recovered from the site, another interesting characteristic is the presence of iron-rich deposits on a number of pottery pieces recovered from the site. The lakebed substrate around the Tsuzuraozaki site is fairly rich in iron, and once the pottery has settled on the lakebed, iron-rich lacustrine deposits slowly begin to form in the area where the soil and water meet. This has resulted in characteristic band-like iron deposits on some of the pieces. While more recent pieces have a thinner metallic sheen, some of the deposits on the older Jomon period pots are quite thick. By looking at the shape and orientation of the iron deposits, researchers can gather information regarding the orientation of the pottery on the lakebed, and in some cases can determine that some sort of repositioning occurred due to multiple iron deposits bands on the pots. To gather this data, scale drawings were made of many of the pieces held at the Tsuzuraozaki Lakebed Historic Remains Museum by Yano and his students. The position and orientation of iron deposits were recorded as well as color changes in the pottery which were recorded through the use of Minolta SPAD-503 Soil Color Reader. In addition to the scale drawings, a digital recording approach was used in the form of photogrammetric 3D scans of several pottery pieces from the site. This paper will provide an overview of that process, discuss how the initial data was recorded, and how that data was then processed into 3D models. The paper will conclude by explaining how those models were further processed to provide realistic digital models of the pottery, and then a discussion of the project results and how the recorded data from the project can be used for further research.

Material and Methods

Materials

During the initial scanning sessions, sixteen intact pots or pottery pieces dating from the Middle Initial Jomon period to the Early Kofun period were scanned for this project. All scanning for this project was conducted at the Tsuzuraozaki Lakebed Historic Remains Museum. For the photogrammetry capture, a Sony a7R IV mirrorless camera was used along with a variety of lenses of different focal lengths, either 20mm, 35mm, or 55mm. A Godox AD1200 flash unit paired with a Godox R1200 ring flash was used for lighting. A custom-made polarization filter holder was used to attach a sheet of linear polarizing film to the flash unit, and circular polarizing filters were attached to the camera lenses in order to take cross and parallel polarized images, the process of which will be explained in the following methods section. The camera was mounted on a sturdy tripod with a geared center column. This helped to avoid unnecessary movement but also provided an easy way to raise and lower the camera to some extent without adjusting the tripod legs. Both a Syrp Genie Mini 2 automated turntable as well as a 50cm Comxim turntable were used to help automate the capture process. A second tripod with a geared center column was used to mount the Syrp Genie Mini 2. A Godox x5 Wireless flash unit was used to connect the camera to the flash initially, but this was later changed for a direct wired link. A laptop was connected to the camera to provide a larger and more easily viewable liveview display of the camera framing using the Sony Imagine Desktop program. An XRite ColorChecker Passport was used for color calibration and white balancing. The images were preprocessed using Adobe Lightroom, and the initial models were processed using RealityCapture. Further processing was done using Zbrush, RizomUV, Blender, UVPackmaster, Meshlab, Substance Designer, Advanced Normals to Roughness, and XNormal.

Methods

Turntable Scanning and the Void Technique

For proper photogrammetric capture, images need to be taken of an object from a large number of different positions. Sufficient overlap between the images is necessary to align the cameras in 3D space. This can be done in a number of different ways, but a popular method for scanning small to medium objects is to use an automated turntable. For this approach, the object is placed on a turntable, and once the desired camera framing is achieved, the turntable rotates in predetermined distances, pausing between rotations. The camera is triggered at each of these positions until a complete rotation is completed. This allows for the overlap of images in the horizontal plane to be easily adjusted and done in a repeatable manner. Once a complete rotation is finished, the vertical relationship between the camera and the object being scanned needs to be adjusted, ensuring that a sufficient amount of overlap is maintained during this repositioning. The camera may also be moved closer or further away from the object as the height is adjusted in order to maintain a consistent distance from the object to avoid significant changes in exposure or camera framing. This process is repeated several times, ensuring all portions of the object being scanned are viewable in the images taken. Once the sides and top of the object have been photographed, the bottom of the object needs to be scanned as well. Flipping an object over changes the positional relationship between the object and the turntable or stand that it is resting on however, which can prevent the subsequent camera positions from being aligned. There are two main ways to overcome this problem. One is through the use of image masking, essentially using image processing software or the photogrammetry software itself to mask out anything in frame other than the object being scanned. The photogrammetry software uses these masks to determine what information should be used while processing and what information should be ignored. A second method of dealing with this problem, and the one used in this project is to use a form of "in-camera masking", referred to as the "void" technique (Christiansen 2020).

This technique uses cross polarized lights to filter out extraneous light and relies on a connected camera flash or flashes to expose and isolate the object being scanned. The background of the object should be as dark or as black as possible. For the backdrop itself, standard black backdrop material can be used in most cases. By increasing the distance between the object being scanned and the backdrop, the intensity of light hitting the backdrop at any particular area can be reduced, making it appear completely black when photographed. The platform and area immediately surrounding the object being scanned is somewhat more difficult to deal with as the distance between them and the object cannot easily be increased. These objects should be covered in as dark and non-reflective material as possible. Black felted material works quite well for this, and there are some specialty materials made by companies like KoPro (Koyo Orient Japan) which are especially designed to reduce reflected light and work especially well in these contexts.

Equipment Setup. Images were taken in an open area of the Tsuzuraozaki Lakebed Historic Remains Museum as shown in figure 1. A black backdrop was set up against the wall and the tripod for the camera was set up several meters away. The camera and flash unit were connected either by the wireless flash unit or were directly connected using a PC sync cable. Using the wireless flash unit would occasionally result in the flash failing to trigger. This could significantly slow down the capture process, so the wireless flash unit was eventually replaced with the direct wired connection which resolved these problems. The camera was connected to a laptop using a usb cable. Using Sony's Imaging desktop program, we were able to get a live view from the camera displayed on the larger laptop screen and were also able to adjust camera settings remotely. This was especially helpful when the camera was set at its highest positions where the camera screen was difficult to view, and the controls were difficult to access. Initial tests were done with the RAW images being saved to both the SD card in camera as well as to the connected laptop. Unfortunately, the large file sizes coming from the camera and slow transfer speeds to the laptop would quickly saturate the connection and stop image captures. To compensate for these issues settings were changed to either send lower quality jpegs to the laptop or to avoid saving copies on the laptop at all.

Two different turntables were used during the Tsuzuraozaki pottery scanning, a smaller Syrp Genie Mini 2 turntable and a larger Comxim turntable (Figure 1). The Genie turntable would connect directly to the camera using the Sony multiport and was controlled by a bluetooth app. The Genie was smaller and could easily be mounted on a tripod, allowing for the height of the turntable to be easily adjusted, but the size of the objects that could be safely scanned on the turntable was somewhat limited. For larger objects the Comxim was used. The Comxim was connected to the laptop and controlled with Turntable X, the program provided by the company. The turntable could not be mounted on a tripod and instead had to be placed on container boxes brought to the museum. The height of the turntable could not be adjusted so all height adjustments needed to be done using the camera tripod, which involved many awkward adjustments of the camera legs.

Figure 1: Photogrammetry capture process using the Comxim turntable (left) and the Syrp Genie Mini 2 (right)

Camera and Exposure Settings. With the backdrop and scanning platform prepared, the next step was to adjust camera settings and exposure. Images were taken in a RAW format in order to preserve as much data and dynamic range as possible. This allowed for more flexibility in adjusting and processing the images later on. White balance was fixed, and an image of a color checker was taken in order to properly set the white balance later during image processing.

For camera settings, the first setting adjusted was the camera aperture. Along with the shutter speed, this setting controls how much light is allowed to reach the camera sensor, but aperture also has a significant role in the depth of field (DoF) of the image. The depth of field indicates the range of distance from the camera that will be most in focus and is indicated in camera settings as the F-stop. A wider aperture (lower F-stop) allows in more light, but it also creates a shallower depth of field. If the F-stop is increased and the aperture is closed down, less light is let in, but the depth of field is increased. In more artistic photography, a shallow depth of field may be desired, as you are able to isolate the intended target or portion of the target by keeping it in focus while having areas that are closer or further away appear unfocused and blurry. For photogrammetry this is the opposite of what we would want, which is to have the whole target in focus if possible. To further increase the depth of field of an image, the distance between the target and the camera can be increased, but this causes additional problems. If the flash being used is connected to the camera, increasing the distance between the target and the camera will result in a darker exposure, which will need to be compensated by either increasing the flash output power, decreasing the shutter speed, or increasing the camera ISO. The target will also be taking up less space in the frame, providing less information from which a 3D model can be constructed. On the other hand, if much of the target is out of focus, it can be difficult to align features between camera positions and can result in softer, less detailed textures in the 3D models. The ideal range for maximal sharpness is typically around F8, with ranges from F8 to F11 often used in photogrammetry. Moving settings above F11 will usually have a negative impact on image sharpness, but this again needs to be balanced against the impact of image sharpness when much of the object is beyond the camera's depth of field. At maximum F-stop levels, diffraction can cause a significant deterioration in image quality and should be avoided if possible.

With the distance between the camera and object and the aperture setting decided, the next step was to adjust the shutter speed and ISO. As stated before, the shutter speed helps to regulate the amount of light that is allowed to reach the camera sensor for each image taken. In addition to its role in adjusting camera exposure, the shutter speed also regulates the amount of motion blur in an image. A fast shutter speed allows for light to reach the camera sensor for only a brief period of time. This short duration means that less light is getting into the sensor, reducing exposure, but in limiting the time that light is allowed to reach the sensor it reduces the capture of movement in the image. A good example may be of a sports photographer appearing to “freeze time” in their images through extremely fast shutter speeds. A landscape photographer on the other hand may want to use slower shutter speeds, allowing for more movement to be captured in the image, such as the flow of water down a waterfall or along a coastline. Turntable photogrammetry allows for a reasonable amount of flexibility in terms of shutter speeds. Having the camera on a tripod can allow for slower shutter speeds, but the speed should be set enough to ensure there is no motion blur in the images while still letting in enough light to be able to properly expose the images.

The last setting to adjust was the ISO. The ISO setting adjusts the light sensitivity of the camera sensor. Higher ISO values increase the light sensitivity and lower ISO values decrease the sensitivity to light. Higher ISO values are often advised against as increasing the sensor sensitivity can start to introduce noise into the image, but advances in camera sensor technology have allowed for properly exposed images to be taken at higher ISO values without appreciable noise in the images. Post-processing software has also significantly improved, allowing for noise to be significantly reduced in images if necessary. Taking this all together, exposing images properly at lower ISO settings will ensure enough light is getting to the camera sensor and will reduce the likelihood of noise significantly impacting image quality, but raising levels slightly above the normal base ISO of 100 shouldn’t have a significant impact on image quality.

Returning to issues related to the void technique, with an appropriate aperture setting in place, several test images were taken without using the camera flash with the goal of adjusting the camera settings so that the image appears completely black. We ensured that the cross polarized/linear (CPL) filter was rotated so that it was perpendicular to the filtered light coming from the flash. An easy way to do this was to place a metallic object in frame and take a picture. You then rotate the filter on the lens and take another picture. When the image is fully cross polarized the metallic object should appear mostly dark, as specularly reflected light is cut by the cross polarized filters. With the filter set in the correct position, the sensor sensitivity was set to the camera's base ISO level and the shutter speed was adjusted as necessary. Setting the base exposure in this manner ensured that extraneous lighting in the area wasn't affecting the images taken in any meaningful way.

With the base exposure set, the next step was to adjust the camera settings when the flash was being used. The power settings on the flash will depend on the power of the flash being used, the distance to the object, and the recycle time of the flash unit. Running a flash at full power can increase recycle times, reduce the number of shots that can be taken before the battery runs out or the unit begins to overheat. The Godox AD1200 is fairly powerful, so flash settings were typically set between full power and ¼ power without any real concerns of slow recycle times or overheating. If it did become an issue, decreasing the shutter speed and increasing the ISO settings would help to compensate for lower flash outputs, but before starting the actual capture process an additional test image without the flash should be taken to ensure that lights other than the flash unit are not interfering.

Capture method. With the basic setup and camera settings in place, the next step was the actual capture process. The basic capture process proceeded as described in the turntable scanning section. Pottery pieces that could stay upright on their own were placed directly on the turntable. For pottery with pointed bottoms a raised ring covered in black felt was used which helped to avoid needing to do any additional masking of support structures. For pieces with uneven bottoms, bead-filled bags covered in black felt were used to help prop up portions of the pottery. These provided a soft support for the pieces that were flexible enough to form to various shapes and heights.

When the pieces were safely positioned, several image "rings" were taken at varying heights. To adjust the positioning the artifact on the turntable was carefully lowered and the camera height was raised using the geared center columns on each tripod. If additional height was needed the camera tripod legs would be adjusted as necessary. Once the sides and top of the pottery was captured, it was turned upside down and additional image rings were taken, lowering the camera or raising the turntable with each image set. The typical image ring consisted of 20 images, or rotation steps of 18 degrees. For objects with fairly simple shapes and few self-occluding areas, a rotation step of 20 degrees can often be sufficient. For more complicated objects, the number of images per full rotation should be increased so that occluded areas are captured with multiple images. Complete pots were more difficult to scan than ones missing their bottoms like the one shown in Figure 2, as additional images and more closely spaced image rings were necessary in order to view the interiors of the pots. When the scanning process is completed there should be a fairly even distribution of images taken from around the object with every portion of the object viewable in at least three images (Figure 3).

Figure 2: Jomon period pot missing bottom portion

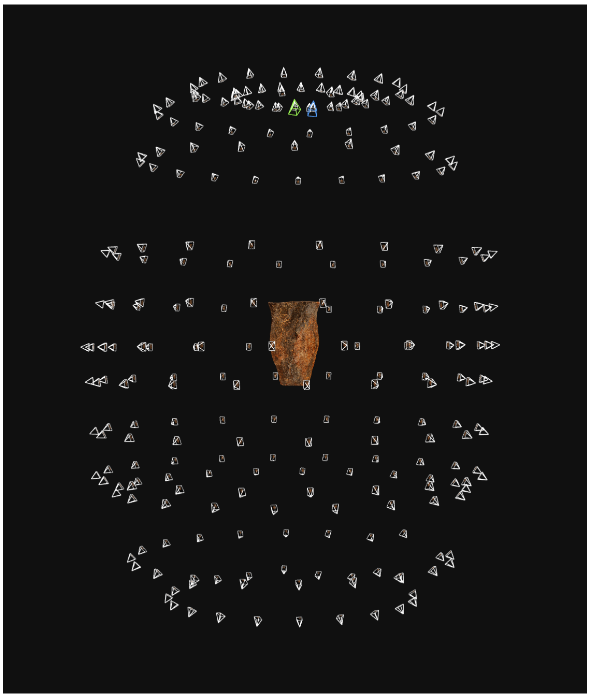

Figure 3: Image rings from turntable scan

Cross and Parallel Polarization Capture. As mentioned earlier, on some of the older pottery the iron-rich deposits were quite thick, but on more recent pieces the initial stages of iron deposition could be seen in the form of a somewhat metallic sheen on certain portions of the pots. In order to try to capture this phenomenon on some of the pots, two photo sets were taken for each photo ring, one using cross polarization and one using parallel polarization. Cross polarization helps to cut specular reflections from images, but in these circumstances the reflections themselves were an object of study. To capture these reflections the polarizing filter on the light was rotated 90 degrees, allowing for the capture of parallel polarized images. While some degree of reflection was still cut from these images, the inclusion of parallel polarized images ensured that at least some of those reflections could be captured. A comparison of cross polarized and parallel polarized images can be seen below in Figure 4.

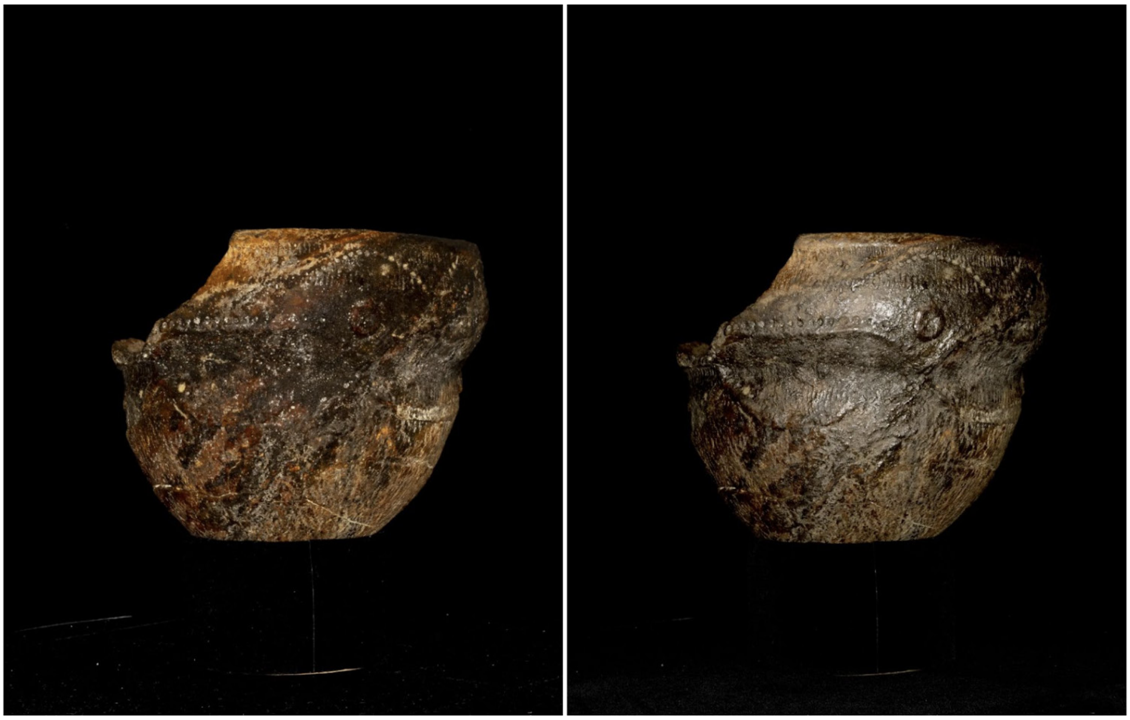

Figure 4: Left: Cross Polarization Example; Right: Parallel Polarization Example

In normal circumstances reflective objects can be very difficult to scan well using photogrammetry. The photogrammetry software relies on the identification and matching of contrast points and gradients, and the shifting locations of reflections can cause the alignment process to fail. When both a cross polarized image set and a parallel polarized images set are taken, the cross polarized image set can be used to help with the base alignment and the parallel photo set can be used as a separate texture layer. These layers can be used later on in post processing to help improve the realism of the resulting models, a process which will be discussed later on in the paper.

Image Preprocessing

Once the initial images were taken, the next step was to preprocess the images before importing them into the photogrammetry software. RAW images typically need to be preprocessed and converted into a format that is compatible with the photogrammetry software being used. During this process there are some additional steps that can be taken to help ensure that the images and resulting model are as accurate as possible to the original object. These steps aren't absolutely necessary to create a 3D model and some of them were not enacted until later on in this project, but they should help improve the end product.

As mentioned previously, RAW files help to capture as much data as possible from the camera sensor, and we can now use this to our advantage during this preprocessing stage. For this project most of the initial image processing was done in Adobe Lightroom. Images were first selected and imported into the program. The next step was to select the image with the color checker, proceed to the development tab, and adjust the camera profile setting. These profile settings will interpret the data in the RAW image file and provide the visual output that is displayed on the screen. As part of this interpretive process, the color rendition of how the images are displayed can be adjusted in a number of ways, for example emphasizing certain portions of the spectrum in order to make a more vibrant image. With the goal of trying to render the colors as true to life as possible and extracting out as much data from the images as possible, applying a linear profile to the images was a useful first step. This helps to provide a fairly flat and even rendition of colors in the images rather than over-emphasizing or under-emphasizing certain colors in the image. Using the void technique can result in a lot of the areas that appeared to have been completely black in the images becoming visible, which will be dealt with later on in the processing.

Once a profile was applied, the next step was to set the white balance for the image using the color checker patches in the image. There are a number of software packages intended to help further adjust color accuracy which could be used if desired at this point. For this project, however, only the basic steps of the applying a custom linear camera profile created using DCamProf and adjusting white balance using the color checker were taken to achieve reasonable color accuracy.

The next step was to adjust image exposure. Assuming that the camera settings weren't changed in the middle of shooting and the distance between the camera flash and the object being scanned was fairly consistent, the exposures of all the images should be fairly similar. Although there are better ways to ensure correct exposure, the base exposure setting process for the Tsuzuraozaki pottery was done in a manner referred to as exposing to the left (ETTL). Normally when setting exposure, the general goal would be to ensure that there is no clipping present, which would be when the portions of the image are either too bright or too dark to be fully displayed. In the context of turntable scanning in the void, there is typically a significant amount of movement left or right (exposing darker or lighter) that can be done before clipping occurs. Exposing to the left or making sure that the start of data being displayed on the image histogram was close to the left side without clipping provided a relatively easy convention for adjusting the exposure of images in the event that the distance from the object or some camera settings had been changed mid scan. It also helped to avoid major differences in brightness between the different pottery scans. While this method provided some degree of consistency, the exposure of the objects when placed in a 3D renderer may not be consistent to what is expected for a realistic result, which requires additional changes to model textures after the fact. The exposure of later scans at the Tsuzuraozaki site were set based on the middle-gray patch on the color checker, which had the benefit of keeping exposure levels between scans more consistent.

Although this sets us with a base exposure level for a relatively accurate color portrayal, one of the goals of the void technique is to mask everything out of the image but the object being scanned. This requires a different approach to exposure and color settings which will be applied in a different image layer. To ensure that the area surrounding the scanned object is cut from the image, the exposure, shadows, and black sliders in Lightroom needed to be reduced. Changing the settings to visualize clipped areas of the image was an easy way to visualize this and adjust the levels as necessary. Reducing these levels too much could result in parts of the pottery being scanned to be clipped as well, so care needed to be taken when making these adjustments. While this process helps to mask out the background and isolate the object being scanned, it is also changing the color of that object.

In order to be able to record reasonably accurate color data while at the same time ensuring that the in-camera masking process was successful, separate image layers were created. One set of images was exported before the color levels were adjusted as a texture layer, and another set of images with the making adjustments included was exported as a geometry layer. This process works slightly differently depending on the photogrammetry program being used, but the basic concept of using multiple image layers is the same. As the ideal layer for feature detection and camera alignment can differ significantly from an accurate color portrayal, this ability to use multiple image layers can be very helpful. This also comes into play when dealing with cross and parallel polarized image sets, as once the cameras are aligned, separate cross polarized and parallel polarized images textures can be created from the same model.

The last step in the process was to sync the changes to all images in the set for each image layer and export them in a new format. For the basic geometry layer jpeg images set at 100 percent quality were used and should suffice to provide enough data for feature detection and feature matching. For the texture layer, tiff formats will offer a higher bit depth and lossless compression, providing the highest quality image for texture creation, but they come at the cost of having very large file sizes in comparison to other formats. For example, the Sony a7R IV has a 61MP sensor and RAW files from the camera are typically around 120 MB in size. When the RAW files are exported as jpegs processed at 100% quality they end up around 20 MB each, while the same file exported as a tiff can reach up to 350 MB in size. While tiff files may provide slightly better color information, for many it may not be worth the additional storage space. For the initial scans done for the Tsuzuraozaki project tiff texture layers were used, but due to the amount of storage space these files use, later models were made with jpeg textures.

3D model Creation

Alignment

Once the images were processed and exported into usable formats, the next step was to import them into the photogrammetry software. Different image layers were saved into separate folders. RealityCapture has some specific guidelines as to naming conventions in order to be recognized as separate layers. For this project, folders were named "_geometry", "_texture01", and "_texture02". The image folders were imported into the program and the initial alignment was started. If all images aligned, the next step of meshing was started. If most images aligned, but some were not able to be aligned on the first attempt, alignment was attempted again. In RealityCapture, multiple alignment attempts can result in additional images being aligned with the main component if initial attempts were not fully successful. In circumstances in which multiple alignment attempts fail, manual control points were used to connect separate images or components with the main component. Both the automatic alignment attempts as well as attempts where manual control points are placed can sometimes result in misalignments, where different components are connected to each other in orientations or positions that do not reflect the actual scanned object. Before proceeding to meshing, it's important to ensure that the camera positions are properly aligned. If multiple alignment attempts as well as manual intervention with control points are still failing to properly align the images, alignment settings such as using a lower image overlap setting or allowing for a greater reprojection error can sometimes help to align particularly difficult scans. If these steps fail as well then processing a new set of geometry images and repeating the alignment process is likely a last resort. The images taken during the Tsuzuraozaki pottery scans had a generous amount of overlap and typically aligned without many issues. Some of the darker pieces did have some initial problems with the way the exposure and black levels were set and required additional processing to successfully align.

Meshing

After alignment was completed and verified, the next step was to mesh the model. RealityCapture offers three levels of meshing: "draft", "normal" detail, and "high" detail. The "draft" level will produce a meshed result the fastest but does so by downscaling the images by a factor of four, providing a result that is the lowest quality of the three settings with the lowest polycount. The "normal" detail setting downscales images by a factor of two, and the "high" detail setting processes the images at full scale. While "draft" setting results do well at providing quick visualizations, they aren't very well suited for final end products. The choice between "normal" and "high" detail modes can be more difficult though. While the "high" setting will provide the highest level of detail and the highest polycount, it is often much larger than can be used normally, providing polycounts greater than other programs can handle without needing to decimate the mesh into a more manageable size. Depending on how large the end-result model is, meshing at “normal” detail level can sometimes provide similar end results faster and without needing to significantly decimate the model later on to make it a more functional size. The Tsuzuraozaki models were typically processed at “high” settings and needed to be simplified before export.

The simplification process can be done within RealityCapture and is fairly straightforward. Models can be simplified to a target polycount or they can be simplified by a set percentage. The issue of how best to simplify models in ways to retain the shape and features of the original models can be complex and really deserves its own separate discussion. If using RealityCapture alone, taking an iterative simplification approach of reducing model size by something like 50% multiple times will likely provide better results than a direct simplification to a much lower polycount level, but this again will depend on the particular project at hand and the goals of that particular project. In an attempt to retain as much or the original shape and features as possible for the Tsuzuraozaki pottery, the models were initially simplified in RealityCapture in 50% steps and were then exported and brought into Zbrush for further simplification. While the simplification process in RealityCapture mainly consists of setting the amount of simplification/decimation to be applied and perhaps some amount of smoothing, Zbrush offers a much more comprehensive suite of tools to aid in this process. Although Zbrush is able to effectively manage higher polycounts than most 3D modeling programs, it still has its limitations. For the computer hardware being used for the Tsuzuraozaki scans, simplifying models down to around 60 million polygons in RealityCapture before importing them into Zbrush ensured that Zbrush was able to function without any major problems. For the Tsuzuraozaki pottery models, a combination of polishing crisp edges to define sharp features, decimation using Decimation Master, and reprojecting details were used to try to keep the decimated form and features as close to the original as possible. Although it required additional processing, this process provided results that were visibly better than could be obtained through simplification in RealityCapture alone.

Once decimation was complete the models were then exported for scaling. For the initial set of scans, the scaling process was done using Meshlab. Using scale drawings of the pottery as a reference, points were chosen on the scale drawings and measured. The same points were identified and measured on the 3D models. A scaling factor was calculated by dividing the real-world distance by the Meshlab unit distance. This scaling factor was applied in Meshlab through the Transform: Scale, Normalize function found in Filters -> Normals, Curvatures and Orientations -> Transform: Scale, Normalize. Uniform scaling was enabled, and the calculated scaling factor was entered into the X, Y, and Z spaces. When the scaling was completed, the model was exported for UV unwrapping and subsequent texturing. This scaling process was updated in later scans to include scaled targets that could be automatically detected and applied in RealityCapture, simplifying the process and allowing accurate scale throughout the model processing.

Initial Texturing

The main portion of the texturing process inside the photogrammetry software involves the UV unwrapping of the model and then the subsequent application of color and normal information to the newly created model. RealityCapture allows for several different UV unwrap settings to be adjusted, such as the unwrapping according to prescribed texel size, adaptive texel size, or by maximal texture count. It also allows users to set the maximum and minimum size of the texture map to be created. The process is fairly quick within the program, but often resulted in somewhat poor use of UV space and an overabundance of small island segments. In order to try to maximize the texture quality of the models, the Tsuzuraozaki models were UV unwrapped and packed using two separate programs, RizomUV and the UV Packmaster plugin for Blender.

RizomUV allows for very granular control of UV unwrapping settings which can help to mitigate distortion. To match the 3D geometry with a 2D texture, the 3D geometry needs to be flattened. This flattening process involves the compression of some areas and the stretching of others. A common example of this is the Mercator map, where the sizes of land masses in the north and south of the planet are portrayed as significantly larger than they are in actuality. This is due to these areas being stretched out in order to fit the 3D dimensions of the planet on a 2D map. RizomUV has settings to allow one to choose whether it would be more preferable to have fewer, yet larger UV islands that display a greater amount of distortion or whether it's better to have a larger number of smaller islands that display less distortion. As each island requires a certain amount of edge padding to avoid bleed over to other islands, more islands can result in a greater amount of unused space in the form of these buffer areas. On the other hand, larger islands may have sections of greater distortion where parts are overly compressed or stretched which can affect the visual quality of the model. In addition to these settings, RizomUV also provides a useful visual reference to show this compression and stretching on the maps and allows the user to make additional manual cuts to the UVs in order to reduce these distortions.

Once the UV maps are cut and unwrapped, they must be packed into the desired UV layout. An 8k texture size was chosen for the diffuse (color) maps and normal maps when possible to provide a greater degree of visual fidelity. This can increase file sizes and load times, but these concerns were outweighed by the desire for a better visual representation of the pottery. To that end, the additional step of using a separate UV packing program was decided upon. UV packing programs use algorithms to test different scales, translation (positions), and rotations of UV islands in order to provide the most efficient use of space possible. The UV Packmaster plugin in Blender is a very fast packing program that includes a GPU-based algorithm that is able to calculate these permutations at a significantly faster pace than most other packing programs. While the UV space utilization differences between RizomUV and UV Packmaster weren't significantly large, UV utilization was typically able to be improved using the UV Packmaster program. When this process was finished the newly cut and packed UVs and the associated models were saved and reimported back into RealityCapture.

In RealityCapture the newly processed models were textured using texture reprojection. This is a process of applying or "baking" texture information from one 3D model to another. For the Tsuzuraozaki scans higher polycount models were textured using large 16k textures to be able to record as much texture information as possible. This texture information was then applied to the new decimated and UV unwrapped models, ensuring that the more color accurate "texture" layer was used for processing instead of the "geometry" layer. In the cases where both cross polarized images and parallel polarized images were used, two separate textures were reprojected onto the new model, one for each set. In addition to the color information, normal mapping information, which allows for the appearance of additional bumps and dents in a model without them being a part of the actual model geometry, was also projected onto the simplified models, allowing their geometry to appear more detailed than it actually was. In addition to these diffuse and normal maps, additional maps to further help improve the visual fidelity of the models were created, the process of which is introduced in the following section.

Model Post Processing

In addition to the earlier diffuse and normal maps created for the pottery models, additional cavity, ambient occlusion (AO), roughness, and specular maps were created to increase the realism of the models. Both the cavity and ambient occlusion maps were created in the program XNormal. Without going into too much detail, both cavity maps and AO maps aim to portray the presence of darkened lighting conditions in the cracks or crevices of a model, with cavity maps typically displaying sharper characteristics and AO maps providing a softer appearance. In situations where real-time ray traced or ray cast shadows are unable to be created, these maps can help provide the illusion of shadows in these concave areas of the model.

The roughness and specular maps helped to indicate more polished surfaces of the pottery or areas where more subtle iron deposits had begun to form. The roughness maps for the models were created in Adobe Substance Painter using the Advanced Normals to Roughness plugin. This program utilizes data from normal and height maps to estimate and approximate the location and degree of roughness on a model. An area with a high degree of the differentiation of normal directions in a confined space would be interpreted as being rough, while flat areas with very little differentiation in normal directions would appear to be smoother.

For the specular reflection map, two methods were used. If both a cross polarized and parallel polarized image set were produced, the cross polarized set was subtracted from the parallel set and the result was reduced by 50 percent. This method aims to capture the difference in reflectivity between the cross polarized and parallel polarized view of the model and provides some measure of reflectivity of the pottery in different areas. If parallel polarized photo sets were not present, the previously created roughness map was inverted, and the intensity was reduced to a visually appealing level. This method isn't really measuring any true degree of specular reflectivity, but it helps to break up the specular pattern in a fairly logical manner when casually viewed.

Results and Discussion

At the end of this project a set of models made to look as "photo realistic" as possible were completed (Figures 5 and 6). In all, a total of 5,964 images were taken, with over 15,000 processed images used in the creation of these models. The purpose of these models was to serve as a record of the original pottery in their raw form and as an interactive presentation of these pieces that would be accessible to the public. A careful recording and analysis of the iron deposits on the pottery provides information as to the positioning of the pottery on the lakebed, whether it is likely to have moved to a significant extent during that time, and also provides some understanding as to how long the pottery might have been in that position.

For the public, these models allow people to interact in ways that would be impossible to do in person. The location of the Tsuzuraozaki Lakebed Historic Remains Museum is somewhat remote, making it difficult to see these pieces in person. Even if an individual was able to visit the museum in person, the pieces are fairly fragile, especially the iron deposits, and allowing the pieces to be handled by visitors would likely result in them being damaged (Figure 7). In their glass cases they can only be viewed from a distance and whatever resides on outside of a visitor's viewpoint would normally remain a mystery (Figure 8). In addition to the virtual access to the materials, the 3D data can also be used to create accurate physical representations of the materials as shown in Figure 9. While the 3D data is not currently accessible to download, if the decision is made to release this data in the future anyone with a 3D printer would be able to create their own physical copy of these important pieces of cultural heritage. Although these digital models are not the same as the original pieces, the likeness between the models and the original are unmistakable, and their digital recording and the subsequent sharing of these models allows a greater degree of access to the materials than would otherwise be possible (Figure 10).

Figure 5: Left to Right, Top to Bottom: Kitashirakawa C-type Jomon deep pot (北白川 C 式深鉢), Takashima-type Jomon deep pot (鷹島式深鉢), Ōmugida-type Jomon deep pot (大麦田式深鉢 , Kishima-type Jomon deep pot (黄島式深鉢), Yamadabira-type Jomon deep pot sherd (山田平式深鉢), Middle Yayoi period tsubo pot, Middle Yayoi period pot, Kitashirakawa C-type Jomon deep pot (北白川 C 式深鉢)

Figure 6: Left to Right, Top to Bottom: Late-Middle Jomon deep pot, Late-Early Jomon deep pot, Funamoto-type Jomon deep pot (船元式深鉢), Late-Initial Jomon pottery sherd, Late Yayoi pot, Middle Yayoi pot, Late Yayoi pot, Early Kofun Period Hajiki pot

Figure 7 (Top Left): Fragile deposits on pottery
Figure 8 (Bottom Left): Pottery pieces exhibited behind glass
Figure 9 (Right): 1/2 scale and 1/6 scale models created using a resin 3D printer

Figure 10: Comparison of rendered model and digital image from display case

The overall process of scanning and processing these models was a learning process. Some lessons learned allowed improvements to be made mid-project, while some will have to wait until future projects. Improved color management later on in the project helped to greatly improve the color accuracy of the models. The improved utilization of UV space helped to improve the visual quality of the end products. While they were not able to be included in the initials scans of this project, the later inclusion of scale bars in later scans provided more accurate scale measurements and avoided the sometimes-difficult task of matching features between the 3D models and scale drawings. Due to the differing size of the pottery scanned, maintaining a constant distance between the camera, flash, and pottery was impossible, but later scans included the use of a laser distance measure which ensured a better control of initial image exposure helped avoid some of the later adjustments and guesswork necessary during image processing and model postprocessing. Finally, while the texture image layers for this project were exported in tiff format, more recent projects have been shifted to using 100% quality jpeg files. The visual difference between the two are negligible or nearly impossible to spot and the space savings by using jpegs instead of tiff files is significant. Since the original RAW files are saved, if for some reason additional image sets are needed with higher quality settings, any lost color data in the jpeg files will still be present in the original RAWs.

Future research

Throughout the course of the project, techniques and approaches to the scanning process improved and the quality of scans and the speed at which they are processed will only increase in the future. Sixteen pots is only a small portion of the current collection of pottery recovered from the Tsuzuraozaki site and work continues in order to attempt to scan the remaining pieces at the Tsuzuraozaki Lakebed Historic Remains Museum. With the capture and initial processing of these sixteen models completed, the next step is exploring additional use cases for the digital materials. Additional consultation with officials is planned to discuss additional ways that these can be used to benefit the community associated with the site and the public in general. To that end, some initial work on ways to better visualize and contextualize the remains has already been started and are explained below.

Color Ramping

As previously explained, the process of creating a 3D model involves creating a geometric copy of the original model to which texture maps are applied to add visual elements such as color, specular reflections, and shadows. While these additional elements help to make a model look more realistic, it is often easier to view and understand the 3D shape of a scanned object before these texture maps are applied. However, even when these additional textures are removed, the clear visibility of features is often view dependent. For this reason, I wanted to try to create additional model versions that would allow for shape characteristics of the models to be viewed more easily regardless of the viewing angle.

A common method for achieving this is through the use of color ramping. Color ramping is a method to apply a range of colors to an object based on specified attributes. A familiar example may be an elevation map, with higher and lower elevations portrayed using a chosen spectrum of colors. While difficult to see in the grayscale images in Figure 11, color ramping applied to the upper images still helps to highlight differences in thickness in different areas of the pottery. Color ramping has been used extensively in 3D visualizations and is often

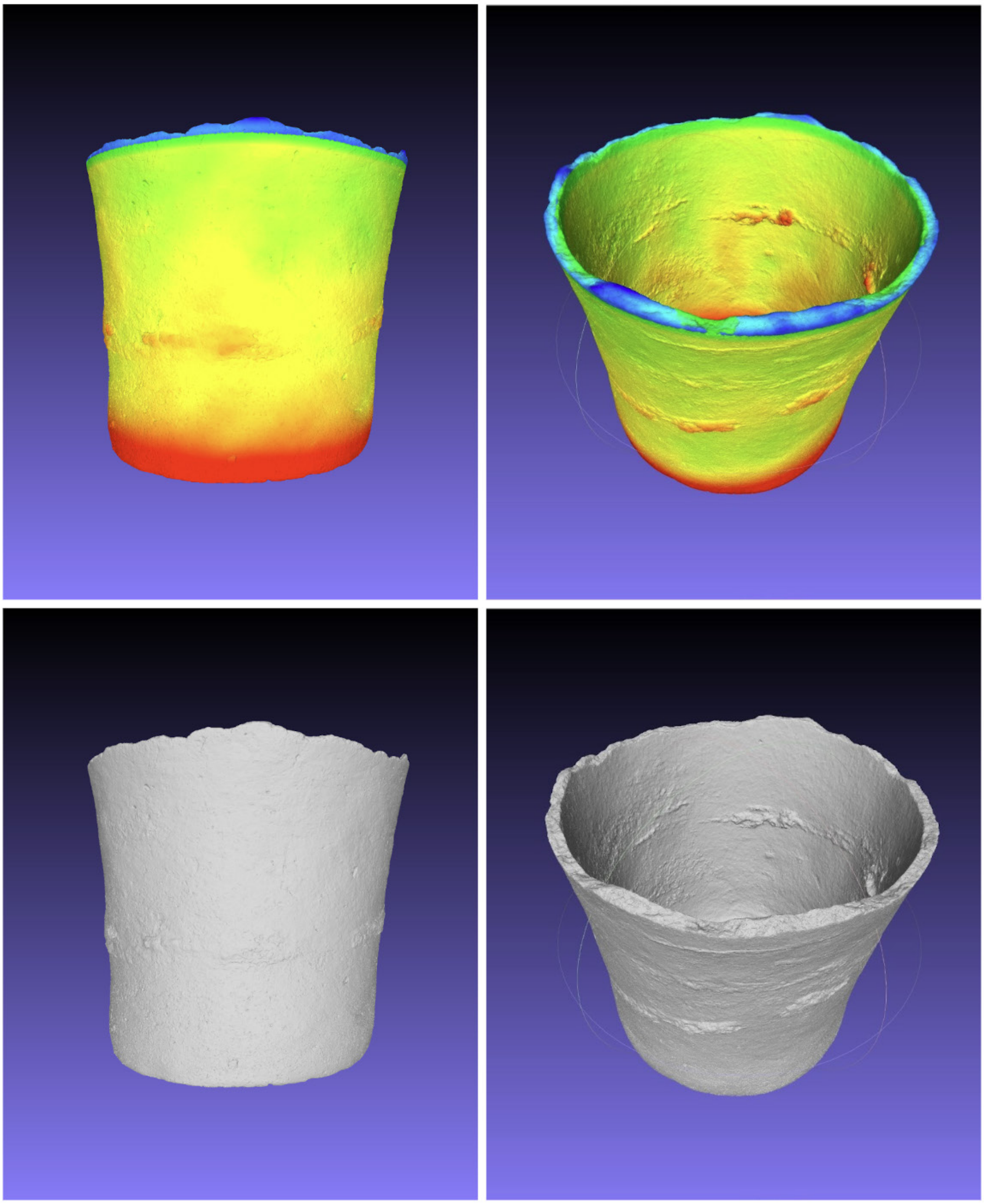

Figure 11: Top: Color ramped comparing Inner and outer surfaces; Bottom: 3D model without additional applied textures

seen in geometric morphometric (GMM) studies, but 3D GMM studies of ceramics is still a limited field. The initial concept of the color ramping approach being tested on the Tsuzuraozaki pottery comes from work by Loftus and Seguchi (2022). 3D scanned pottery was first digitally unrolled and then a scalar field projection measured the distance from a fixed plane to the front of the pottery. The process was further refined with sliced segmental extraction (SSG) which divides this unrolled model into smaller sliced sections and measures these slices individually. Variability in the shape of the pottery that could not be visualized when examined as a whole can be more easily identified when each slice is analyzed and visualized separately (Loftus and Seguchi 2022). While this improved method can better detect shape variability on the surface of pottery, the measurements are still taken from a single side and the overall thickness cannot be determined due to similar shape variations on the inside of the pots. This is especially true for much of the Tsuzuraozaki pottery and their thick iron deposits.

I have been testing a few methods to both improve the visualization of features through color ramping as well as to measure the actual thickness of the pots by separating the inner and outer surfaces. To measure the thickness the inner and outer surfaces are separated and the distance between them is calculated using a nearest neighbor calculation in Meshlab as shown in the top of Figure 11. To better visualize the features on the inner and outer surfaces without variations on the opposite surface interfering I have been testing additional methods of simplifying the surfaces and using those as a reference mesh to measure against (Figure 12). The methodologies are currently being refined, but initial results are promising.

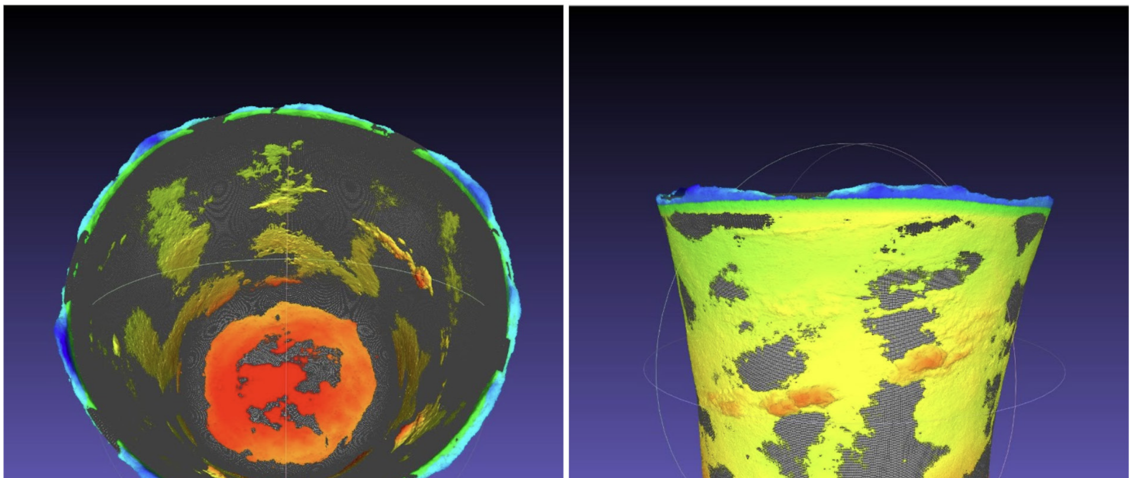

Figure 12: Color ramped images shown with smoothed reference meshes

Depositional Context

The second approach to better understanding the pottery from Tsuzuraozaki involves providing a better view and understanding of their contexts. The pottery held in the Tsuzuraozaki Lakebed Historic Remains Museum was collected long before the more current investigations of the site using robotic submersibles, so we don't have the same sort of imagery to show how these artifacts were positioned and oriented on the bottom of Lake Biwa. However, using the position and orientations of the iron deposits on the pots we can create a digital representation of what they might have looked like sitting on the lakebed floor for hundreds or thousands of years (Figure 13). These recreations can help provide a better understanding of the process in which these iron deposits accumulated on these artifacts to the general public and possibly help to generate more interest in the Tsuzuraozaki site and its long history.

Figure 13: 3D model of a scanned Kofun period pot visualized on the bottom of Lake Biwa

Conclusion

The world is experienced in three dimensions, but throughout most of the history of archaeological research, the recording and documentation of archaeological materials in many ways has been limited to just two. Advances in computing and imaging technology have now provided archaeologists with the ability to better record and explore the world using that third dimension than ever before. As 3D scanning methods like photogrammetry become more commonplace in the field, the next steps are to further expand our research horizons and push beyond the limitations of the past. We should be aiming to improve the quality of models, improve the ways in which they are shared and saved, and expand the ways in which we interact, utilize, and learn from them.

This project was started with the aim of conducting a thorough recording of pottery from the Tsuzuraozaki site and by and large it has been successful in that pursuit. Great care was taken to try to record these pieces as well as possible. The geometric details of the pottery were captured well, the colors are quite accurate when compared to the original pieces, and even the varied reflectivity of the pottery was able to be recorded to an extent. The process took longer than originally expected, and not as many pieces were scanned as we might have hoped but approaches and techniques improved over the course of the project, which will help to improve additional scanning projects in the future. The methods of this capture process and the discussions of its successes and failures were shared in the degree of detail that it was in order to help others continue to further push the boundaries of this process. Beyond recording, deeper consideration and more discussions are needed regarding the additional utilization of archaeological 3D assets as well as creating defined digital management strategies to ensure the accessibility and preservation of this data in the future.

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3D Model Creation and Processing of Tsuzuraozaki Lakebed Site Pottery

by

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One hundred years ago marked the first official recognition of the Tsuzuraozaki submerged lakebed site in Shiga prefecture. Since that time locals have continued to pull up a number of largely intact pottery from the site in fishing nets and researchers have sent divers as well as underwater robotic submersibles to examine and better understand the site. In 2022 a new project was started to conduct a thorough examination of the pottery recovered from the site, including 3D scans of some of the pots using photogrammetry. Lacustrine iron-rich deposits present on a number of the pots recovered from the Tsuzuraozaki site provide a unique challenge in terms of the accurate recording of the shape and color of these pots which digital recording methods like photogrammetry appear well suited for. This article provides a thorough explanation of that 3D scanning process, explaining how equipment was set up to photograph the artifacts, how camera settings were adjusted and the reasoning behind those adjustments, how images were processed prior to 3D model creation, a description of the 3D model creation process itself within the photogrammetry software, and the final postprocessing and texturing of the 3D models with the goal of creating as realistic looking models as possible. The results of the process are shared and are followed by general discussion regarding the project and some future projects related to these initial 3D scans.