PROCEEDINGS OF SWBSS 2021

Fifth International Conference on
SALT WEATHERING OF BUILDINGS AND STONE SCULPTURES

22-24 September 2021
Delft, the Netherlands

EDITED BY
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TU Delft OPEN

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MICRO-PHOTOGRAMMETRY TO MONITOR SALT IMPACT ON PETROGLYPHS

Andrew J. Thorn[1*], **and Ben T. Collie**[2]

KEYWORDS

Micro-photogrammetry, delamination, crypto-fluorescence, micro-spalling

ABSTRACT

A project focusing on the potential industrial impact on a cluster of one million engraved boulders in a remote desert location, requires, among other metrics, the study of micro-spalling because of potential crypto-fluorescence, or surface deposition, both of which change the surface morphology at the micro-scale, including pre-spall swelling.

Project outcomes include deploying technologies readily implemented in-field, ultimately by locally trained operators.

This paper outlines the system, including the operation of a portable fully automated triaxial scanning frame and the processing technologies deployed to produce a 3D photogrammetric model, and the further processing of that model to provide long-term indicators of change.

All three axes are programmed to scan with a single button press, gathering up to 5,600 images over the target within 150 minutes. To acquire fully focused Z-axis images, a stack of 20 images is acquired at 1 mm vertical intervals. The other dimensions are set to image any given point 4-9 times, depending on the overlap.

System screening identified a 36Mp DSLR fitted with a Zeiss 4x objective as the most effective imaging system, including being an existing piece of field equipment used for other studies, only requiring the addition of the objective and its mount.

The Z-axis image stacks are processed through Helicon Focus to reduce the 5,600 images to 250 stacks, submitted to Agisoft Metashape for model construction. The model is interrogated using various measurement programs including CAD, Metashape and Cloud Compare to establish vital change metrics.

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1 INTRODUCTION

Salt, in its simplest chemical definition, is the reaction between an acid and a base. In the context of this conference salts are typically deliquescent species or less soluble types, both disrupting the surface and altering its appearance. In a five-year study of the interaction between industrial gaseous by-products, the atmosphere through which they travel and an exposed rock surface upon which they interact, change is being measured, chromatically, elementally, and dimensionally. The multi-disciplinary study includes atmospheric modelling and measurement, together with laboratory focused geological, bio-geological and microbiome studies. This photogrammetric system has been designed to model a group of approximately one million engraved boulders in a coastal desert location in Western Australia. The engravings have been pecked and abraded into a relatively soft weathering rind formed on the surface of gabbro and granophyre type igneous rocks.

The authors are responsible for in situ change metrics including colorimetric, elemental, and topological change. While all three techniques combine to measure change, only physical dimensional change is described in this paper. This project requires that all metrology be non-contact or minimally so, where it can be demonstrated to be non-disruptive to the surface.

To measure short term dimensional changes requires a detailed scan of the surface at reasonably high resolution. In general surveying, laser scanning provides more accurate results than photogrammetry, however accuracy is a function of distance from target to sensor. Optical profilometry can achieve sub-micron Z-axis resolution, but traditionally has required the sample to be brought to the instrument. More recently portable options are emerging [1]. In the current study image acquisition is achieved through a Zeiss 4x objective attached to a 36Mp digital SLR to operate approximately 70 mm from the surface with a 20x14 mm framing, providing less than 3 micron per pixel resolution. This compares to typical macro-lens-based photography, which is typically 80mm across [2] .The key is that the system can be carried to the object, and the object can be of any dimension and in any orientation.

Despite its reduced operating distance, the objective-on-camera system allows for very close-range imaging and when attached to a microprocessor-controlled scanning table acquires surface topography over an area of any desired dimensions.

The technology will be fully described, however due obligations to the custodial community and the contract, the site will not be discussed.

2 THE AIMS OF THE STUDY

Industrial impact is being assessed in a multi-disciplinary study, due to concerns expressed by several observers that rapid change has occurred or will occur to the visibility of cultural markings. One component of this study is the in-situ metrology of change to the surface, including colorimetric, elemental, and morphological change. Within the three in-situ metrics, morphological change is being monitored through annual modelling campaigns over five years initially to determine to what extent the surface is undergoing alteration. Colour change has been seen in previous studies as the primary indicator of change, however this can only be determined if the physical integrity of the surface is confirmed. The loss of one mineral grain or ephemeral precipitate may distort the colour and this can only be confirmed through a detailed study of the surface. More relevant to the theme of this conference, surface disturbance may take place with only micro-morphological change. This would occur where delamination and crypto-florescence are just beginning to develop within the surface. Of course, ephemeral efflorescence will alter the colour quite markedly and sporadically.

To record morphological change a system has been refined to capture the three-dimensional morphology in sufficiently fine detail and to provide comparative alteration data over time.

The cultural markings can be more than a meter in length; however, they all have a more or less consistent engraved channel no more than 50mm wide and up to 20mm in depth. For that reason, a study area of nominally 100x100 mm has been chosen to embrace the engraving detail and sufficient surroundings to include reference markers and related deterioration features, such as the extensive delamination occurring on many surfaces. Monitoring of delamination rates, while readily discernible, forms part of the documentation obtained through this study.

3 INSTRUMENTATION AND METHODOLGY

Due to the remote coastal desert location along the north west coast of Western Australia, system design has started with site constraints, worked its way through the transportation pathway and arrived at the laboratory. Photogrammetry has been chosen over other techniques because it is relatively compact, provides readily readable real-world imaging and relies on an extensive set of primary images that separately serve as very useful documentary records.

Various early implementations have been trialed, including a stereo microscope with both DSLR and digital imaging devices fitted. A 16Mp microscope digital imager with purpose made lens was also considered for its auto-focus benefit, however auto-focus is challenging for any macro-photography even with suitably high frame rates. Similarly, several microscope objectives were tested, with the 4x giving the best compromise between magnification and depth of focus. Plan achromatic lenses are chosen for their flat image, without requiring the fastidious colour correction of the more expensive Plan apochromatic colour balanced optics.

3.1 Image acquisition

The approach requires image acquisition in-situ using a Zeiss 4x NA 0.1Plan-achromatic objective fitted to a Pentax K1 36Mp full-frame DSLR using a standard objective mount. Such mounts remove auto-focus functionality, which shapes the scanning protocols described below. Plan achromatic objectives give the flattest, most in focus image of any optics, whereas the achromatic feature is sufficient for non-colour critical applications, as colour change is measured spectrometrically.

Images are acquired in .jpg format only as this gives the same level of sharpness as RAW image reconstruction, the superior colour control of the latter not relevant to the study. Much finer colour metrics are achieved through a detailed Spectrophotometric study. File transfer is done manually at the end of the image acquisition cycle, although Wi-Fi syncing is available. Up to 5,600 36Mp images are acquired, requiring 155 Gb SD storage. This increases to 264Gb for a 61Mp sensor. A camera with two SD slots makes this manageable.

The photogrammetric processing, covered in the next section, relies on some of the exif (exchangeable image file format) data from the image, importantly the focal distance of the lens. Focal distance is that between the object and the imaging sensor focal plane, neither of which is recorded in the adopted optical configuration. For a camera lens the focal distance can be approximately measured when a light beam is in focus on a sheet of paper when shone through the lens. A microscope objective is more difficult to measure, however the sharpest light beam is a reasonable measure. The focal length can be set in the camera manually and is usually asked for where a manual lens is connected to the body. The only additional adjustment is to tell the camera, through the settings, that an extension ring is in use.

With this configuration the objective has a 70mm working distance, providing an image frame 20x14mm. The objective can be fixed further out of the mount to produce a frame 16 mm wide at a working distance of 55mm from the surface. A 5x objective has been tested with the wide view reduced from 16 to 6mm, considered closer than necessary for the detail sought. The 36Mp sensor provides approximately 360 pixels per millimetre (2.8microns per pixel) for a 20x14 image, increasing to 460 px/mm for 16 mm wide image 2.2 microns per pixel). The program plans to migrate to a 60Mp mirrorless camera, providing better image stability at high resolutions and a pixel density approaching 600 px/mm. While depth of focus is difficult to precisely quantify, a 2mm tall text on a flat sheet of paper is sharp through approximately 4 mm of focal travel. Contrasting with this is the heterogeneity of the surface to be studied, which includes natural undularity and the cultural channel depth, requiring the objective to travel up to 20 mm, although greater travel and bracketing can be programmed into the Arduino controller very simply.

Photogrammetry protocols usually stipulate a 60% overlap between frames to allow for full stereoscopic reconstruction of the Z-axis. A 60% overlap ensures that any point on the surface is imaged four times. Setting the frame overlap to 40% ensures that the same point appears in nine images, as indicated in figure 1. This additional coverage, at a cost of a 20% tighter scan yields 225% image density, resulting in better resolution of the 3D model.

Even at the shorter 55 mm focal distance the camera is no more than 19° from vertical, and while this is sufficient to produce good stereoscopic resolution the camera mount includes a graduated rotary baseplate for precise rotation of the camera to provide more oblique views. To benefit from off-set camera views requires a double scan to capture the scene form both angles. The downside to running an automated double scan is the extra demand on power and storage, together with the doubling of photogrammetric processing.

An efficient alternative would be to run a 60% overlap at a 25-30° offset to left then right, reducing the total image count to around 2/3 of the 40% single pass regime, with better height resolution. Tilting the lens too far will result in reduced in-focus areas in every image.

Surface lighting is controlled in a number of ways. A purpose made filter holder attaches to the objective mount to receive a 30mm polarizing filter and variable neutral density filter. These can ensure that the scene, typically intense clear sky sunlight, is controlled for optimal image production. Conversely a small LED (currently a rechargeable selfie ring-light) is also attached, not to boost light but to soften shadows created by the intense sunlight. Shading is easily provided.

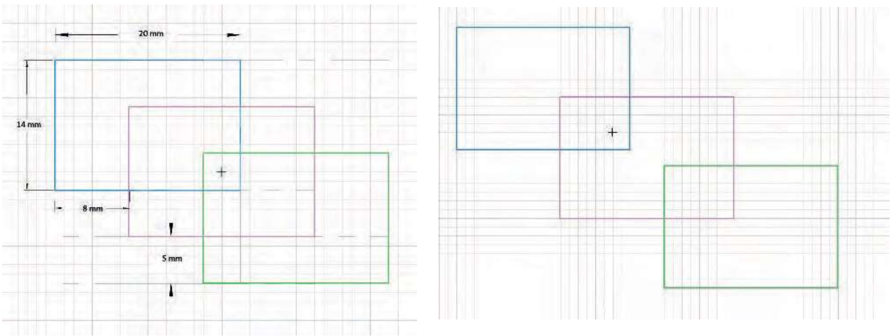

Figure 1: A 40% overlap has been set at left, imaging the target + 3x3 times. At right a 60% overlap reduces this to 2x2 images of the target.

3.2 Scanning frame

To provide a steady acquisition at regular depth intervals and to ensure the traverse across the surface is precisely regulated, a purpose made scanning frame has been constructed. Unlike many other similar scanning frames, the requirements here are that it must be able to be transported by plane, be carried to site by foot and be applied to irregular surfaces of all inclinations from horizontal to vertical, in which case additional support is required. It must also be flexible in how it remains steady on the rock surface, both to meet the custodians' concerns that the surface is not impacted or contaminated and in situations where, for example, a vertical surface may reside tightly up against an overhang that negates support from above.

Figure 2: The microscope on camera positioned above the surface in the motorized frame. Levelling feet maintain a minimal scanning height range across the plane.

The overall dimensions of the frame have been set at 600 mm, providing scan area of 340 x 440 mm. Hence the 100 x 100 mm nominal scan area can be expanded in situations where morphology demands a larger study surface.

The scanner is controlled by an Arduino Uno R3 microcontroller board coupled with an Adafruit Motor Servo Shield to provide precise synchronization between the three motors and the camera trigger, which needs to mesh precisely with the Z-axis increments. The camera is triggered by the board in synchronization with the Z-axis movements, firing after 0.5 seconds to give time for the camera to stabilize. The shutter speed is kept above 1/160th sec. to further optimize sharpness.

The system is powered by a pocket sized 15V battery, regulated in the control box to a constant 12V to provide power to the three motors and any ancillary devices including powering the camera, and LED ring lighting, described ahead, and to charge other low voltage equipment such as GPS and smartphone devices used for the overall survey.

Scanning movement is driven by standard CNC type 8 mm threads with a pitch of 2mm. The X and Y motors rotate at 120rpm, giving the required advances in the lateral dimensions at less than 0.5 seconds. The Z-axis is driven by a 5rpm motor, advancing 1mm steps over a 20mm total vertical travel. The one-millimeter focal range increments are well within the 4mm depth of focus to ensure each elevation is captured in at least four images. Optimizing movements and camera stability ensures the model can be completed in a reasonable time frame of around 2½ hours.

To overcome the lack of autofocus, image stacks are post-processed using focus stacking software, discussed ahead.

Controlling motor incremental movement has been fundamental to achieving a consistent coverage in a timely manner. The highly geared high torque motors are available in rotation speeds of 0.6-220 rpm, with the faster motors losing torque through fewer gears. Rotation is voltage sensitive, and they will run on 3V and lower with proportional rotational decreases. For the purposes of this frame the voltage is regulated to give a consistent 12V, however maintaining uniform scan dimensions requires fine tuning off-site to achieve a regular square. Due to differential orientation and friction in the screw thread, travel back and forth is uneven. This is compensated by programming the outward and return journeys independently. Separate programs have been written for horizontal and vertical orientations as these impose different torque on the motors. The Z-axis motor needs to lift and lower the camera when horizontal, whereas these two movements are more uniformly loaded in the vertical orientation.

With a 3D model it is not important to register individual points on the surface but to keep the scan in a roughly rectilinear shape ensures an optimal scan area. The Arduino board allows for timing intervals down to 1 millisecond and when combined with motor speed control ensures that the movements are timely and smooth. A typical100 x 100 mm scan takes approximately 150 minutes to complete, requiring no attention from the operator, free to carry out other tasks at the site, including condition assessment, non-photogrammetric imaging, and the other two components of the study: XRF elemental distribution and Spectrophotometry.

It is worth noting that both XRF and spectroscopic studies have a spatial component, for which the frame can accommodate any instrumentation to provide precise spatial control. Some instrumentation lacks electronic triggering and hence the vacant fourth channel of the Adafruit motor controller allows for the addition of stepper motor control to a robotic finger press for any button or switch.

3.3 Scanning protocols

Image acquisition protocols start with the recognition that the target area will be re-scanned in subsequent investigations. Once a target area has been chosen the first task is to provide a series of reference images to clearly demarcate the study surface for relocation purposes. These are a series of stepped images from whole site framing down to a close crop of the target surface itself.

Once the study surface is relocated, targets are inserted into the scene at corners off the critical study area. Brass tubing of c.4 mm sides and c.0.45 mm wall thickness is placed, with one longer tube of 50 mm set on a long axis to provide a calibration scale in the final model. These targets are pre-measured using microscopy measurement software, providing calibration to a known dimension. The 50 mm tube is useful in this process as a longer calibration reference provides more accurate mensuration for smaller in-scene dimensions, such as the 4 mm and 0.45 mm dimensions of the targets. The targets can be individually patterned and colored and are generally placed with the tube opening facing the camera. The first target is more precisely repositioned to the previous location to provide a start position for the scanner. Photogrammetry does not require precise re-positioning of every frame, as the final model is the sum of all images, not specific points in individual frames.

With the targets are in place the camera is manually navigated to the start point, typically the far-right hand corner and just below focus. Manual navigation is controlled through the Arduino control board via face mounted control switches for each axis. A single button press starts the scanning to acquire approximately 5,600 images per scan. Before a scan, the camera is driven over the whole study surface to establish altitudes to ensure that the 20mm vertical increments are within the altitude of all parts of the study surface.

3.4 Focus stacking

One of the limitations of microscope objective imaging is the lack of autofocus, combined with a limited depth of focus of approximately 4mm. At these resolutions it can be argued that auto focus is unreliable and even with general macro-photography it is common to apply focus stacking to a series of images acquired at a range of focal distances.

Focus stacking applies an image processing algorithm to a series of coaxial images, with some tolerance for misalignment in the better programs. After evaluating several programs, including the functions in Photoshop, the best and most flexible processor proved to be Helicon Focus™. Focus stacking takes the sharpest details from every image and combines them into one final sharp composite. Inevitably, the result is not as crisp as the most in-focus parts of any individual image, however the overall result is acceptable and will apply to any close quarters imaging technology regardless of technical details. Sharpness of the final model has been evaluated to determine that focus stacking can provide a sharper model than that achieved where the Photogrammetric software does the selection.

Typically, in a stack of 20 images covering a 20 mm focal distance movement, only 6-10 images contain sharp detail, depending on the undularity of the surface. Helicon Focus scans through all images and only selects the useable parts of any that show suitably sharp detail, no matter how small a section of the image, so there is no need to manually filter out blurred images. The 5,600 primary images are condensed to 280 stacked images for photogrammetric processing. Having set the focal length in the camera prior to imaging, Helicon Focus retains this to ensure the stacked image provides the necessary data for photogrammetric processing.

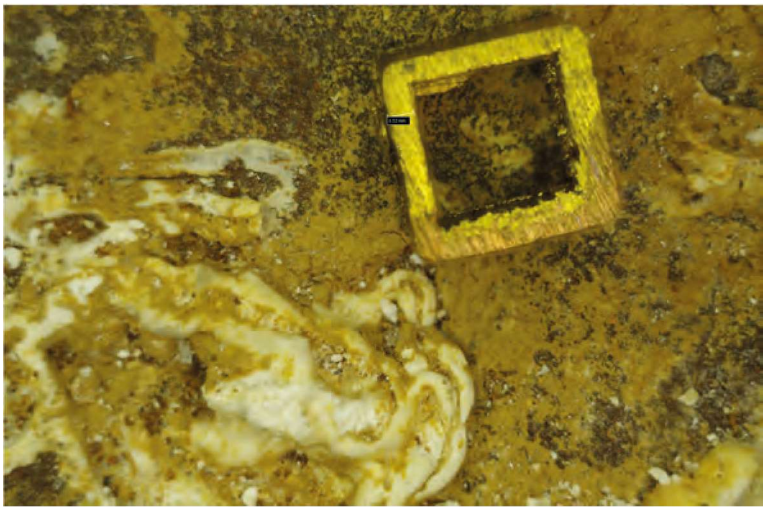

Figure 3: A focus stacked image of one of the 4mm reference targets placed in the scene. Scaling from this target allows for precise measurements within the model. In this example fine details can be discerned that are less than 20 microns wide.

3.5 Photogrammetric model construction

Two programs have been assessed for constructing the 3D model. Agisoft Metashape™ has been preferred over Photomodeller Scanner™ for general photogrammetry due to its ease of use and ready acceptance of images from multiple sources and orientations. Photomodeller can only process images in one orientation and from the one source. While these constraints do not apply to the current imaging protocols, the ease of use makes Metashape a sensible choice. Neither program can process edited images that have lost their exif data.

Photogrammetric model building is all about computer processing power and it is most common to describe upper end systems shaped by budget rather than minimum requirements. Entry level processing requirements for efficient model processing, especially with the very processor intensive Metashape are shared between, CPU, GPU, and RAM. Metashape uses all three but in specific processing stages. Some processes are entirely CPU and others GPU, with CPU required for more than 80% of the processing time.

A computer with 32Gb of RAM, shows that processing a single model requires no more than 16Gb almost all the time. Anything less than 16GB will increase the processing time, however 8Gb would be acceptable for occasional use, whereas 4Gb turns the processing into a multi-day event. The chosen computer has 16Gb of graphics processing (GPU) and all of this can be engaged for some graphics intensive steps. The CPU runs at up to 3.0 GHz and all of this can be required for some processes. There is almost no caching required with the configuration described and the computer has sufficient reserves to allow for other activities including image editing. Two models have been processed simultaneously but this can lead to some bottle necks where both models are GPU or CPU intensive at the same time, leading to some productivity gains but with each model taking longer.

Of the four processing steps: align photos, dense cloud, mesh, and texture construction, the dense cloud construction occupies 80-90% of the processing time and is CPU intensive. Hence a lower spec GPU would not slow down the processing significantly.

Generally, the model is too large to be shared to third party 3D viewing freeware, however that is not its main purpose. The model is intended purely to provide evidence of morphological change.

4. INTERROGATION OF THE 3D MODEL

The three-dimensional model is interrogated in three main ways. The first is simply to observe versions of the target over time.

Metashape Standard has all the processing capability of the Professional version at a considerably lower price. Critical features are lacking however, the most useful being measurement within the model but the entry level program processes with the same resolution as the professional version. Measurements can be taken, at no additional cost, and with some benefits, by using both CAD software and Metashape™, both compatible with some Metashape export formats. The third method for observing change over time is to process time separated versions of the same scan area through Cloud Compare™.

4.1 Observational analysis

Observing the 3D surface is sufficient where the advance of a delaminating edge can be tracked, and changes plotted. While this can equally be observed from individual photographs the 3D model gives a rotatable restituted panorama of the surface at a level of detail not achieved through conventional flat plane imaging. Either the photograph covers the whole area or is so detailed that comparison between adjacent frames is cumbersome. Panoramic stitching can expand the field of view but with planar distortion. The benefit of micro-photogrammetry is its ability to study the surface at the sub-millimetre level, with image readability down to the 10-micron level. This is sufficient detail to observe massive features such as a quartz grain loss or the finer development of precipitates and distortion of a surface through sub-fluorescence pressure.

4.2 CAD measurement

Three-dimensional CAD software can open files saved in several cross platform compatible formats. One of the strengths of photogrammetric models is that they provide dimensional data not measurable line-of-site. Thickness through a solid, for example, can be measured by taking a cross section through the model where the two outer surfaces form the outer bounds of the slice.

In one scenario, the 3D model is sectioned through an engraved channel, using distinct surface features, such as sand grains or other recognizable “landforms” as datum points. The model is sectioned into a very thin ribbon with the two datum features bisected by the slice. The near edge of the slice becomes a precise profile of the contour of the channel. A reference line is struck between the peaks of the two datum points and from this both depth measurements and volume can be calculated using the CAD measurement tools. Loss of datum points is always possible; however, any two points can be established at any time in the history of the study and new metrics established on new datums at any time. While the CAD drawing can be re-scaled to provide real world dimensions, this can also be achieved through off-drawing conversion factors; all dimensions being relative to the reference line connecting the datum points. The distance between the datum points is established by scaling to the inserted brass tube targets.

Such surface changes as micro-spalling or pre-delamination swelling can be measured in this way. The perpendicular thin ribbon view also provides a unique observational view of the profile; visually compared between time periods.

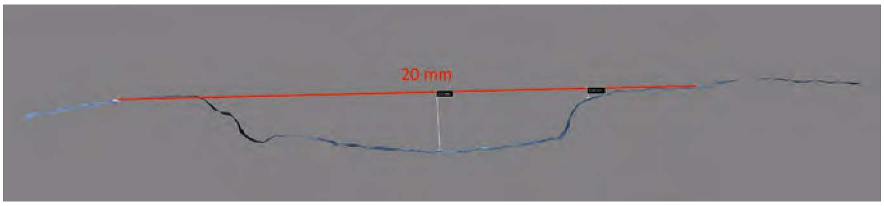

Figure 4: The 3D model can be rotated and sliced to produce a cross sectional profile. In this example to known features are measured to be 20 mm apart. By taking measurements off the line connecting the two reference points, a profile study of the surface contours can be made with great precision. This is most useful when studying spalling and other macro-deformations.

4.3 Cloud Compare

Cloud Compare™ can compare to 3D models, highlighting dimensional differences. It does this through a heat map type visualization with Z-axis mensuration. The benefit of Cloud Compare is that it quickly highlights the entire model’s surface, albeit a 100x100 mm section in this case. The heat map visualization provides quick visual analysis and is best used to target areas of change that can then be further interrogated in more fine detail using the CAD based mensuration approach. Registration of the two models limits the easy operation of Cloud Compare and certainly restricts its stand-alone interpretative value. It is best used as a navigation aid to direct the analyst towards changed areas for further study.

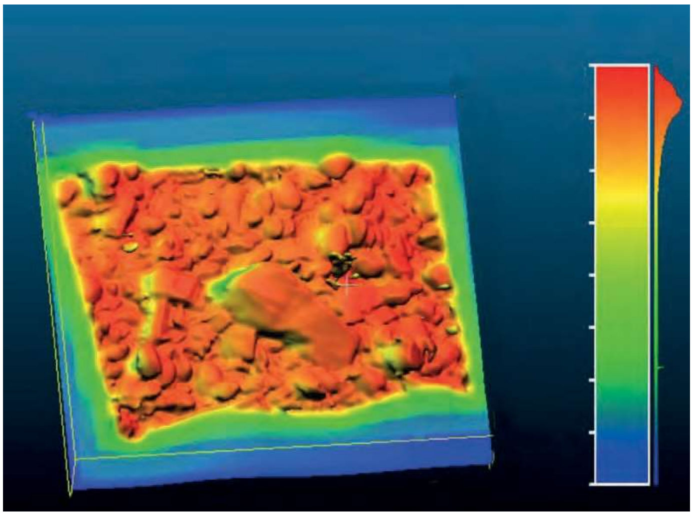

Figure 5: A typical Cloud Compare heat map indication of change, in this case in the Z axis. Cloud Compare is best used as a map indicating areas of change that can better be re-examined within the 3D model.

5. CONCLUSIONS

The system described provides a detailed close study of a surface subjected to erosion through salts and other causes. While the same detail is available through the 2,500 images used to produce the model, it is the ability to study the surface from a range of angles and to further interrogate it through dissection to produce measurable profiles not attainable by physical means. The application of further processing, such as that available through Cloud Compare enable a quick identification of change not as readily discerned by scanning individual images.

All observations are conducted at the sub-millimeter resolution with meaningful observations at the sub-fifty-micron level. Surface features in the range 10-20 microns have been resolved in some situations. This can be compared to ephemeral surface disruption that has been repeatedly observed to be more than 100 microns thick in the project context, and pre-delamination swelling of similar dimensions, where crypto fluorescence deforms the surface prior to rupture.

REFERENCES

[1] D. Ambrosini, T. de Rubeis, I. Nardi, and D. Paoletti "The Potential of Optical Profilometry in the Study of Cultural Stone Weathering", *Journal of Imaging*, vol. 5, no. 60, 2019.

[2] S. Marziali, and G. Dionisio, "Photogrammetry and Macro Photography. The Experience of the MUSINT II Project in the 3D Digitization of Small Archaeological Artifacts", *Studies in Digital Heritage*, vol. 1, no. 2, 2017, pp. 298-309.