



Using photogrammetry to interpret human action on Neolithic monument boulders in Ireland's Cavan Burren



Robin Ann Johnson*, Ariel Solis

School of Architecture and Interior Design, Andrews University, Berrien Springs, MI 49104-0450, USA

ARTICLE INFO

Article history:

Received 6 January 2016

Received in revised form 19 May 2016

Accepted 21 May 2016

Available online 4 June 2016

Keywords:

Photogrammetry

Cavan Burren

Neolithic sculpting

Neolithic monuments

Automatic 3D reconstruction

Virtual manipulation

ABSTRACT

Digital technology has been increasingly employed in the documentation and analysis of archaeology in the last ten years. We utilized user-friendly digital photogrammetry and animation to assist in the analysis of archaeological evidence in Ireland. Our tools were commercially available software, a consumer-grade hand-held or tripod-supported digital camera, and a personal computer. The method was developed for and has been subsequently used by local archaeological surveyors in an extensive documentation of prehistoric settlement features within the Marble Arch Caves Global Geopark in Ireland. The boulder monuments are unusual in that they are made from glacial erratics whose surfaces display traditional North Atlantic rock art and a new sculpting art form. Pieces making up two boulder monuments were digitally manipulated via animation into what is believed to be their original source stone configurations. Their matching surfaces were studied in detail. The process was employed to demonstrate, non-invasively, how the monuments might have resulted from some actions other than weathering. The analysis supports the hypothesis that humans worked the monuments, which, in turn, supports protection of the monuments for further study.

© 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

Heritage sites rich with 3-dimensional, human-worked objects and rock-art surfaces continue to be recorded by scholars through the use of automated digital-capture programs. Multi-image photogrammetry calculates geometric information from large datasets, compares large sets of images simultaneously, and identifies matching features in an accurate, cost-effective, user-friendly manner. Researchers across a variety of archaeology sub-disciplines have increasingly recognized the advantages of combining multi-image photogrammetry, also known as Structure from Motion (SfM) software, with other forms of software to better analyze sites, features, structures, and objects (De Reu et al., 2013).

As an example of a large-scale documentation project, Guidi et al. (2009) integrated multiple tools in a 3D modeling of the Roman Forum in Pompeii by using digital data constituted from aerial imagery, augmented with range data (laser scanning) and terrestrial images (photogrammetry). They established core specifications for data acquisition and modeling, with an independently considered protocol for texture resolution and geometric resolution appropriate for specific artifacts. At a very fine scale, ambient occlusion (AO), a technique employed by video game animators in the entertainment industry, has been used to enhance surface variations to aid in the interpretation of

controversial inscriptions on the Tristan stone (Spring and Peters, 2014).

Animation software can also be used. It was provided automatically as fly-around viewing of digital models in early generations of *123D Catch* software, initially released as *PhotoFly* (Autodesk Laboratories, 2010). However, animation programs can be used more deliberately. For example, McCarthy and Benjamin imported the textured mesh created by Agisoft's (2016) *Photoscan* software into Autodesk's *3D Studio Max* (1999) modeling package and applied depth of field and underwater fog visual effects to create realistic flythrough videos that closely matched the experience of diving in the underwater site of a shipwreck. In addition, they used animation to confirm the match of the fragile silt-filled cannon barrels at the underwater site with 17th and 18th century drawings of a particular make of cannon. They digitally fit the shape of the appropriate cannonball into the digital mesh model of the cannon barrel artifact (McCarthy and Benjamin, 2014).

Animation software in concert with photogrammetry has significant potential to further non-invasive archaeological research. The current paper presents a non-invasive method for inspecting curious repetitive surface formations on monument stones located in the Cavan Burren, an area within the Marble Arch Caves UNESCO Global Geopark, the world's first international Geopark (Parkes et al., 2013). Established in 2000, the European Geopark Network (EGN) is a fast growing aspect of Earth Science conservation aiming to protect geo-diversity, promote geological heritage to the public, and support sustainable economic development through Earth Science based tourism (Gunn, 2009). Open to the public,

* Corresponding author.

E-mail addresses: robinaj@andrews.edu (R.A. Johnson), solis@andrews.edu (A. Solis).

no portion of this Geopark is currently preserved or protected with any special cultural or heritage designation, which is an issue of concern.

The Cavan Burren is an upland karst landscape along the border of Northern Ireland's County Fermanagh but contained within the Republic of Ireland's County Cavan (Fig. 1). Its features include: a variety of stone field walls, both rectilinear (circa 18C) and concentric/radial (medieval or ancient); two classic hilltop wedge tombs, one of which is mostly collapsed and one which remains in cairn (Cummings et al., 2015); a portal tomb retrofitted by 19th century farmers into a calf house; and a dense scattering of significant sandstone boulders (Burns and Nolan, 2007b). Some boulders are grouped in circles. Others are perched on limestone pedestals; some of which have been reduced leaving interesting spaces beneath the boulders. Yet other boulders have clear cup-and-ring rock art motifs, or apparently anthropogenic sculpting, which Burns and Nolan (personal communication, 2012) believe to be a form of early Bronze Age or late Neolithic art.

These boulders, unlike the local limestone material, match the composition of the distant Cuilcagh Mountains and likely were transported during the last glaciation, 13,000 years ago (Lemon, 2010). Due to the high solubility of the limestone, many sandstone boulders are perched on what appear to be limestone pedestals; i.e., the depth of approximately a foot of the surrounding unprotected karst ground-plane has been worn away, leaving only the limestone protected by the overhang of the boulder itself (Lemon, 2010). Some of these pedestals appear to be modified, perhaps by human action, as do some of the boulders (Gunn, 2009). Other arrangements of apparently modified boulders include deliberate splitting and rearrangement of slabs, creation of chambers, insertion of single or multiple chocks, and a variety of other stone arrangements including the addition of kerb stones (Cummings et al., 2015; Kytmanow et al., 2008). Of the 336 boulder monuments known by 2014, 90 are perched on pedestals and 200 are decorated with rock art and/or sculpting (Burns and Nolan, 2007a). Over 100 of

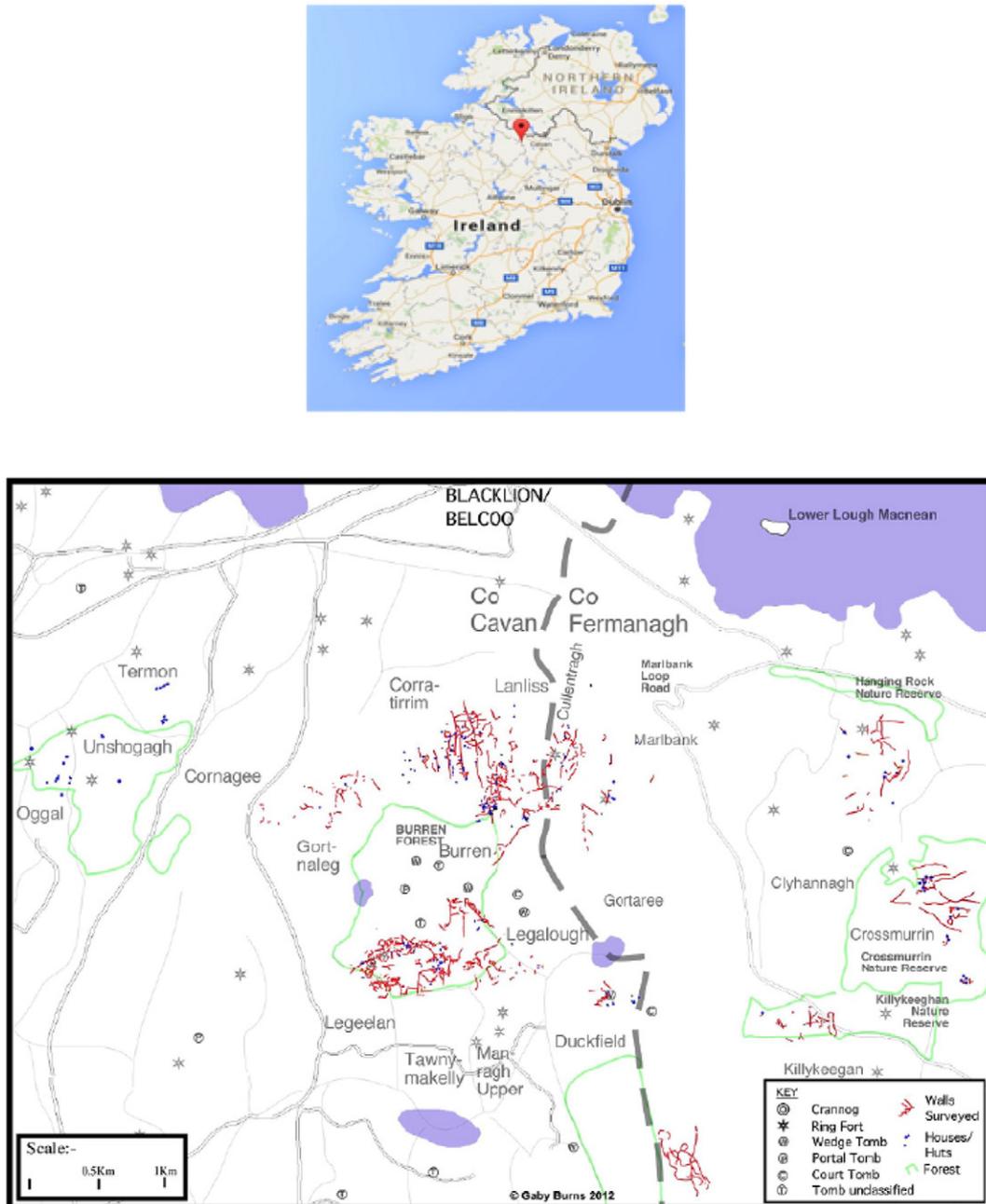


Fig. 1. Location of Ireland's Cavan Burren.

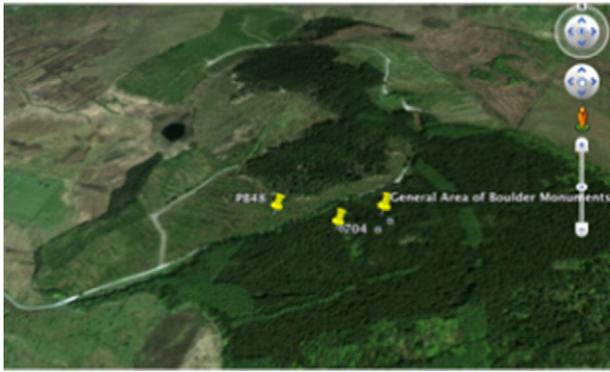


Fig. 2. Cavan Burren Forest Park from GoogleEarth with pinpoints at the ITM references for the monuments. This is a screen shot from the interactive site using the PB48 + 704 ITM Waypoints.kml and the Irish Transverse Mercator (ITM) Grid References: PB48 ITM ref:-607284 834726 and 704 ITM ref:-607396 834682 Irish Transverse Mercator (ITM) is the geographic coordinate system for Ireland. It was implemented jointly by the Ordnance Survey Ireland (OSi) and the Ordnance Survey of Northern Ireland (OSNI) in 2001. The name is derived from the Transverse Mercator projection it uses and the fact that it is optimized for the island of Ireland.

these boulder monuments have now been recorded using photogrammetry (Burns, unpublished), concurrent with our investigation. Clearly, then, the Cavan Burren contains archaeological material worthy of study.

In this case study we describe the examination of two sandstone monuments, each of which bear both weathered and worked areas across their surfaces. The shapes of the pieces in situ suggest they were originally parts of the same boulder, broken apart and shaped by human effort (Burns and Nolan, personal communication, 2014).

Given the potential archaeological significance of the monuments and thus the need to preserve them, it was critical to find a physically non-invasive approach to fully test these hypotheses, similar to approaches used in other significant sites (Barazzeti et al., 2011; Chandler et al., 2005). By using photogrammetric data processed by *Project Memento* (Autodesk, 2014a), and then employing *3ds Max Design* animation software (Autodesk, 2014b) to digitally reposition objects, we digitally re-fit large stones onto the adjacent monuments. Differences in stone surfaces were compared, which demonstrated that significant surface deformation on only one side of the reunited pieces is most likely the result of human intervention.

2. Material and methods

2.1. Geographic and archaeological features of the Cavan Burren

The Cavan Burren is the watershed between the Shannon and Erne River systems, once covered by tropical sea during the Carboniferous period. The Gaelic word *Boireann* means stony place, an apt name given the exposed limestone bedrock lying across the 700- to 900-ft high plateau, 3 km south of Blacklion in County Cavan and northwest of Cuilcagh Mountain. The mountain ridgeline defines the border between Ireland and Northern Ireland.

On this plateau, within the Marble Arch Caves Geopark overlay, is the Cavan Burren Forest Park (Fig. 2) owned and managed by Coillte, the Irish Forestry Board. These 124 ha of mature coniferous forest plantation contain the unprotected archaeological monuments of concern (Fig. 3), and monuments PB48 and 704 (Fig. 4), which we documented in detail.

The lack of either industrial development or intensive land use in the Cavan Burren region, together with Ireland's historically volatile

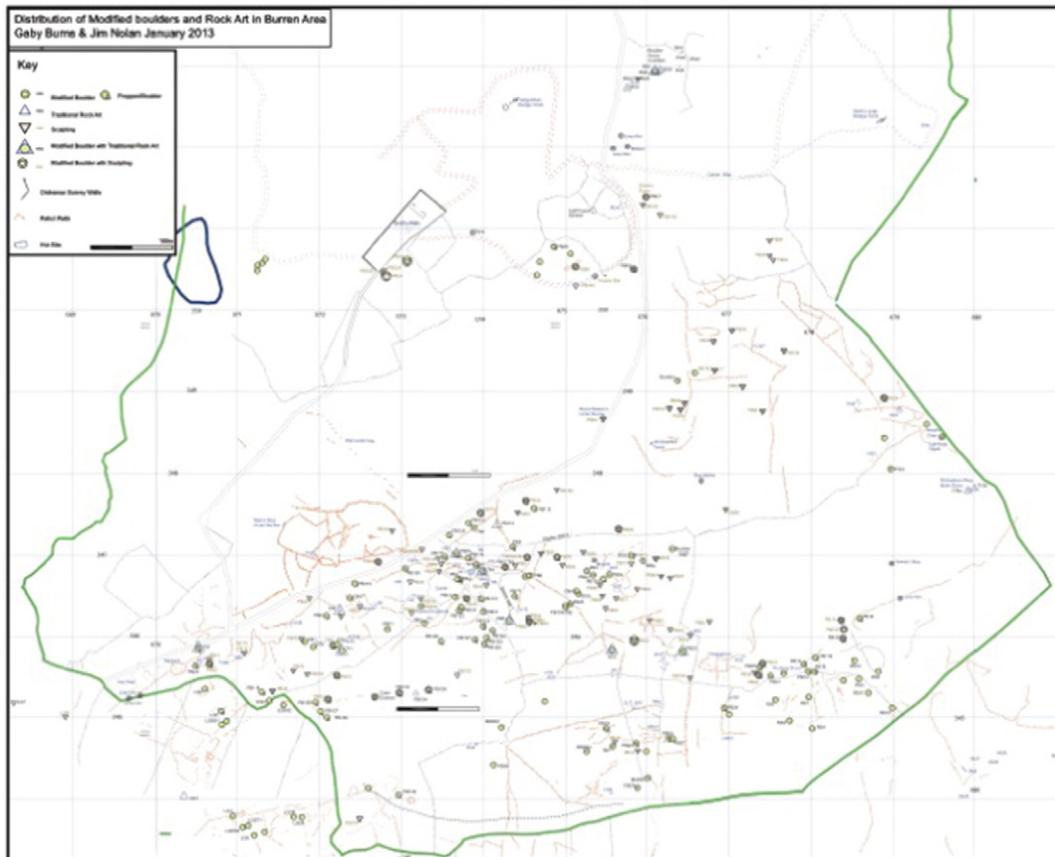


Fig. 3. Detailed map of the Cavan Burren Forest Park with monuments documented by Burns and Nolan as of 2013.

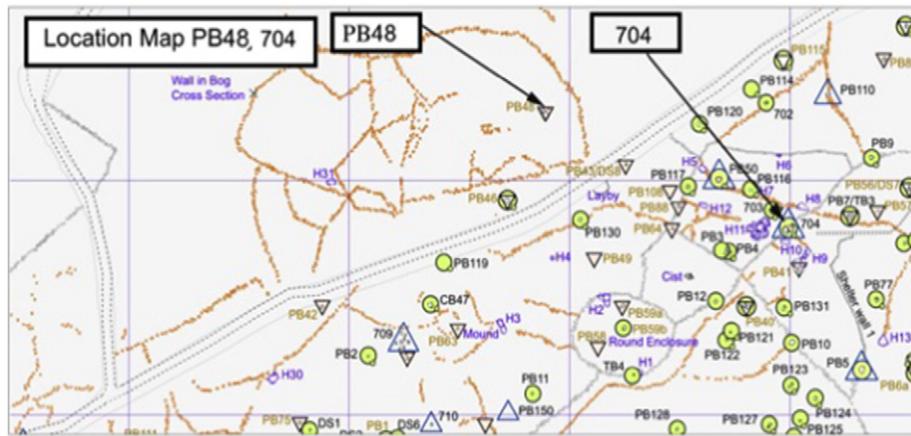


Fig. 4. Enlargement of central concentration of monuments where PB48 and 704 lie.

political landscape (Gunn, 2009), have left this once heavily populated area relatively undisturbed. The local geology contributes to this lack of development with the formation of bogs, disappearance of surface water lakes, (Lemon, 2010), and the dramatic appearance of dolines and swallow holes (Parkes et al., 2013). Government policy of planting trees on large tracts of under-used land throughout Ireland has perhaps helped to temporarily preserve the treasures of the Cavan Burren, but incremental harvesting, since the year 2000, of trees planted in the mid-1900s has exposed and now threatens a broad range of archaeological features (Burns and Nolan, unpublished). Therefore, now that digital laser scanning, photogrammetry, and animation resources are more readily available, it is critical to record and investigate these features before they are damaged or destroyed—an objective congruent with many archaeological efforts in places vulnerable to the public (Clarkson et al., 2014). Such documentation may also aid in preserving the artifacts within this unusual geological landscape.

2.2. Initial analyses of monuments

Our analyses focused on two sandstone monuments: PB48 (Fig. 5) and Monument 704 (Fig. 6). Initially, traditional two-dimensional, free-hand rock art rendering techniques and photography were used to record the monuments. Because the area of interest was significantly three dimensional, the third conventional method used to graphically record rock art, rock rubbing (Stanbury and Clegg, 1990), was not employed. Burns, inspired by the refitting of stones to their source quarries in France (Mens, 2008), had made foil, wire-screen, and plaster castings to check the fit of matching areas between the boulder and its dismembered pieces (personal communication, 2012 and 2015). To record and confirm three-dimensional matches in a less cumbersome

format, we initially used *123D-Catch*, an inexpensive 3D photogrammetry resource by Autodesk (2014c). Our results (Figs. 7 and 8) demonstrated limitations (e.g., photograph megapixel limits producing low resolution, limitations on the number of photographs, difficulty providing reference objects around monument for software stitch-together) similar to limitations mentioned by earlier investigators using photogrammetry software (Chandler and Fryer, 2013; Jazayeri et al., 2010; Remondino et al., 2008), although Bourke (2012) noted that *123D-Catch* can produce acceptable results for more compact forms. One of the most significant limitations of *123D-Catch* was that it cannot process more than 3 megapixels and, due to the complexity of 704, many more digital images were needed to document the entire form.

2.3. Subsequent Project Memento digital processing methods

We continued our investigations using a later-generation cloud computing process from Autodesk in beta form, *Project Memento* (Autodesk, 2014a) that, like *123D-Catch* (Autodesk, 2014c), does not require exacting consistency in the camera position and also redirects the task of processing data away from the personal computer (McCarthy, 2014). Succinctly described by Spring and Peters (2014) in their comparisons of photogrammetry processes for their analysis of the Tristan Stone, the *Memento* product is a high-resolution 3D point cloud or solid surface mesh, generated through a network of computers that process the data and send it back to the user. It employs SfM data analysis from multiple conventional digital photographs, not to be confused with stereo pairs (McCarthy, 2014), and is oriented to make mesh analysis more accessible to artists and professionals in heritage preservation (Spring and Peters, 2014).



Fig. 5. Views of two-piece Perched Boulder PB48, a modified boulder exhibiting sculpted and weathered surfaces.



Fig. 6. Views of three-piece Boulder Monument 704- exhibiting sculpted and weathered surfaces before partial excavation by Cummings et al., 2015. The Cummings team categorized this monument as CV004-059, referred to it as the Cleaven Carraig and, although it bears some characteristic features, determined it was not a portal tomb. No carbon dating was performed, but due to the flake scars on some edges, they believe it to be a Bronze Age artifact.

Our original aim was to effectively and holistically record the artifacts before they were affected by excavation or other more invasive techniques of study and confirm that human handwork had occurred. In a manner consistent with investigations of terracotta warriors from ancient China (Bevan et al., 2014) and inscribed stones from the UK (Spring and Peters, 2014), we sought to document the objects in detail to allow comparisons in shape and context with similar artifacts in the region. Due to the accuracy of the method, we felt that a digital 3D mesh could: 1) provide richer data for studying objects' forms and mechanical origins (Spring and Peters, 2014); 2) establish the similarity of their patterns with patterns in other Cavan Burren artifacts (Bevan et al., 2014); and 3) be used to clearly and noninvasively demonstrate theoretical understanding in a format that can be widely available (De Reu et al., 2013; Miles et al., 2014).

The process involved taking digital photographs of an artifact from which 3D digital models were created. Overall light levels affected the clarity of test photographs, which we reviewed immediately on sight. To compensate for low light levels, we used a tripod. Positioned in a light-filled meadow clearing, a total of 52 images of PB48 were taken with a hand-held camera. Positioned in a fairly dense forest with low overcast light levels, 71 images of 704 were taken with a tripod-supported camera (Fig. 9). The camera, in this case a Canon 7D Mark II with a Canon 10 mm–22 mm lens, was positioned a relatively consistent distance from the artifact in the range of 3 to 4 ft depending on access to the object due to trees or other pieces of stone. Photographs were taken as sequentially as possible from positions around the artifact, with care to overlap areas of the object in excess of 60% to be sure the software could match features seamlessly in its processing. It was not necessary

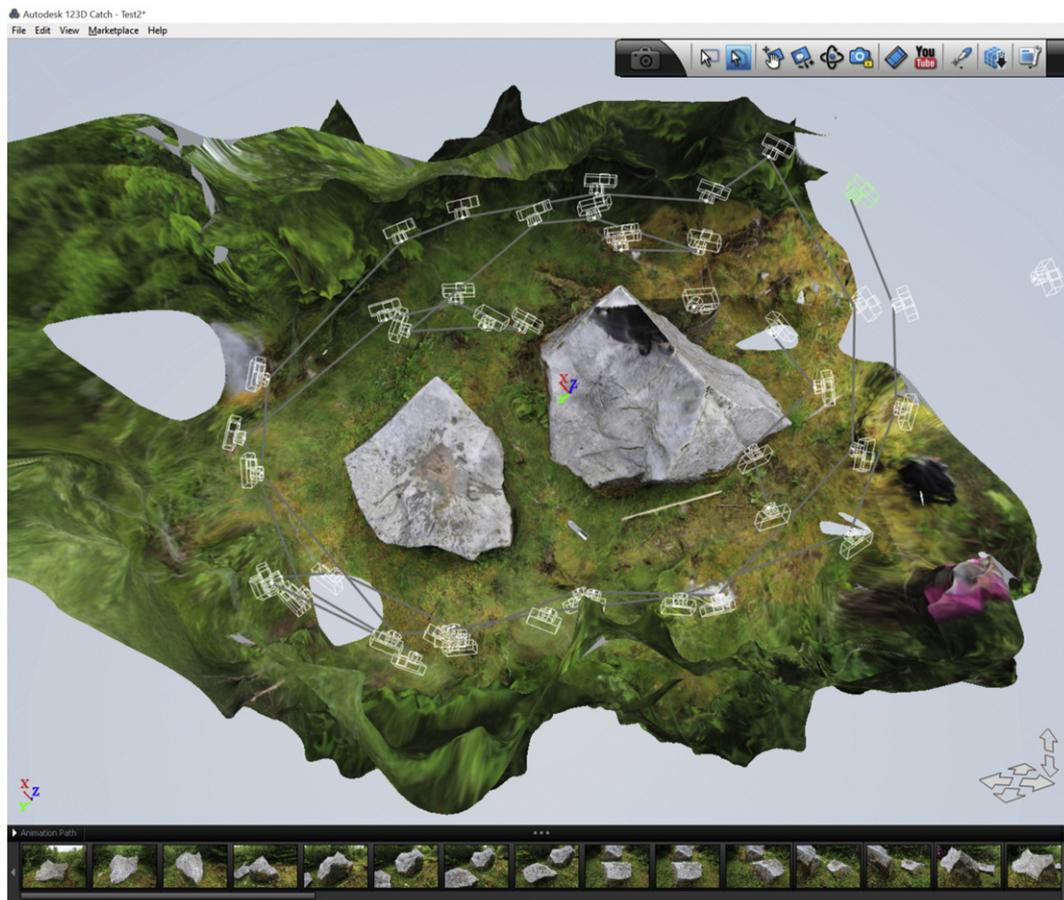


Fig. 7. Views of two-piece Perched Boulder PB48 - showing camera positions of the images as processed by 123D Catch in plan view.

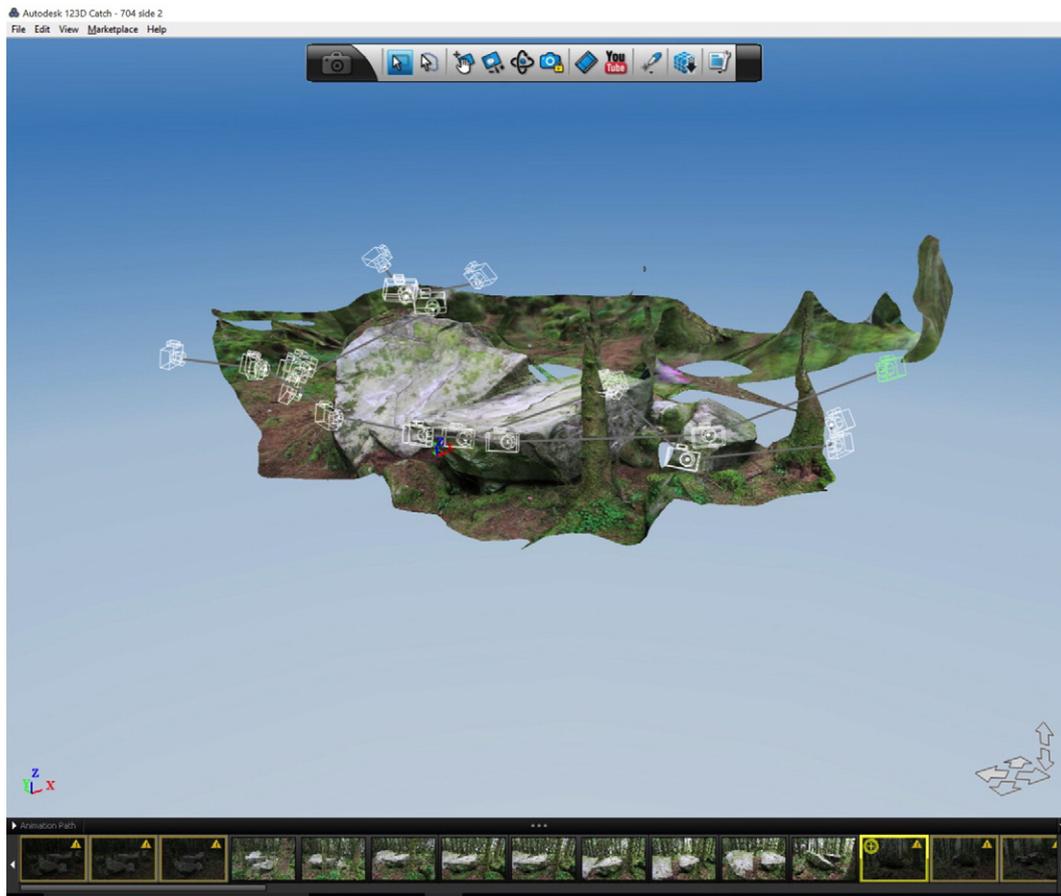


Fig. 8. Views of three-piece Boulder Monument 704- showing camera positions for as many of the 71 images as 123D Catch was able to process.

to place markers or targets on the artifact to aid the image matching software, although we placed a scaled stick near the artifact as a ground control point (GCP) for an absolute scale reference (De Reu et al., 2013), the length of which was given when the images were transferred to *Project Memento* (Autodesk, 2014a) software through the user interface (UI). It was not required that the entire artifact fit into each image, but it was important that all exposed surfaces of the artifact were eventually photographed. Consistent light levels were desired without deep dark shadows, strong highlights, or reflections from surface water.

Depending on the size and the number of pieces making up the monument, several complete circles were made around each monument,



Fig. 9. The photographing of 3-piece Monument 704.

attempting to orient the camera toward its center. Trees and objects blocking view of the artifact were avoided in the photographs as much as possible. It is important to note that the portion of the monument imbedded in the ground cannot be documented this way. Consumer-grade cameras used in concert with multi-image photogrammetry software for partially submerged artifacts is similar to Bourke's description of aerial photography in his exploration of automatic 3D construction, and is more accurately described as a 2.5D reconstruction since it only sees convex surfaces above ground (Bourke, 2012). Despite this shortcoming, what makes our method compelling is the level of accuracy and flexibility of the data resulting from open sourced software, consumer-grade cameras, and minimal photographic skill.

Using our method, the images were then sequentially organized and imported to the UI of *Project Memento* (Autodesk, 2014a), which stitched the images together and sent a notification by email with a link to the compiled 3D point cloud (Fig. 10). We reviewed the stitched-together digital compilation for accuracy and trimmed unnecessary background material. Because the images were not composed to carefully document the background, the background appears distorted in Fig. 10 due to the lack of available feature matches within the photographic dataset sent to the cloud. This is in contrast to the monuments, which were very carefully documented with a scale stick and had sufficient overlap within the dataset. The inclusion of background material in the dataset can slow the cloud processing down, but should not affect the quality of the well documented data unless the dataset causes the cloud to exceed its functional processing limit. There was no evidence that this occurred (Figs. 11 and 12).

The compilation was converted to a 3D mesh with a realistic texture overlay, using Autodesk's (2014a) *Project Memento* software. The resulting photorealistic 3D model can be rotated, tilted, lifted, made



Fig. 10. The 71 photos of 704 stitched together by Memento software before the background is trimmed.

monochromatic or can be observed as if the viewer were orbiting around the model.

2.4. Method of deliberate animation and manipulation of the digital components

To test our theories about how the pieces fit together, we chose to digitally manipulate them. The digital components of the monument were split into individual files (one file for each discrete part), saving each component as a separate OBJ file to enable storage and exchange of 3D data with other software as recommended online (accessed 2015 from <http://www.fileformat.info/format/wavefrontobj/egff.htm>). Each OBJ file was imported into a single scene in the commercial

software, *3ds Max Design* (Autodesk, 2014b), to help the observer perceive and understand the surface and form of the artifact and enable manual repositioning of the digital components (Fig. 13). The OBJ files have the same origin or coordinates, so the *3ds Max Design* software recognizes the x, y, and z axes of the components and their orientation to each other; therefore no hand calibration was necessary. The separate objects were manually manipulated to test how they fit together by selecting the beginning and end positions of certain spots on a given piece. Key frames were created as the piece was moved and these frames were later saved as images. The images that best represent the fit of the parts were selected, and an animation was created in *3ds Max Design* (Autodesk, 2014b) using the appropriate key frames. The information was saved in mpg4 format.

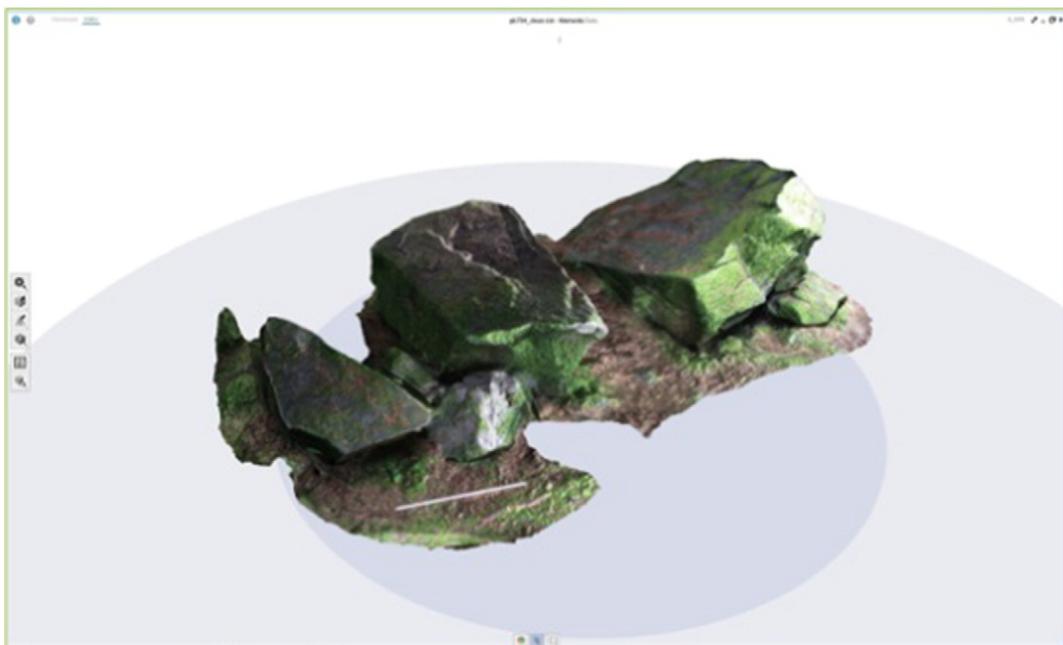


Fig. 11. The 71 photos of 704 stitched together by the software after the background is trimmed.

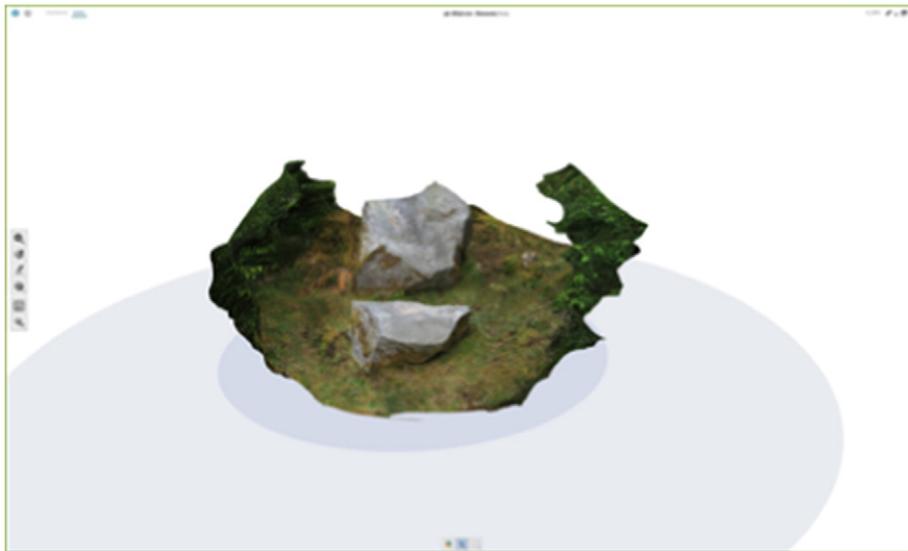


Fig. 12. The 52 photos of PB48 stitched together by the software after the background is trimmed.

The animation was used to investigate and propose the transformation of the boulder. Due to limitations of 2-dimensional communications, like printed matter, still shots from the animation can be extracted and compiled into one image. In the case of Monument 704 illustrated in Fig. 14, 100 images were exported from the animation. The images that best represented the movement of the rock components were selected and positioned in a line. In the case of Fig. 15, selected exported images from the animation were positioned overlapping each other in *Adobe Photoshop CC* (Adobe Systems, 2015). The intermediate positions of the moving piece were toned to differentiate them from the final position of the two separate pieces.

3. Results and discussion

The refitting of PB48 provides significant contrast in once-adjacent stone surfaces. The smaller piece of stone appears to fit over the

monument, as shown in Fig. 16, leaving a fairly consistent seam between the pieces (see number 1). The seam also contains a limited widening of the joint (see letter A), interpreted to be a flake scar or percussion mark, which indicates a splitting of the stone by humans using Bronze Age techniques (Cummins et al., 2015). Some rock surface on both sides of this seam appear to have the slightly convex shape and subtly grained texture (see number 2), identified with the eroded face of weathered stone long exposed to the open air (Giot et al., 1979; cited in Mens, 2008). It can be assumed this was the original stone surface before splitting since this texture occurs uninterrupted on both sides of the seam. The lower stone, designated as monument PB48, has an elongated rounded ridge, which naturally aligns with the surface of the refitted stone piece above it, and can be assumed to be an original weathered texture surface. However, significant gullies appear on both sides of the ridge (see letter B) in an arrangement that bears no resemblance to the upper piece of stone. These gullies have a

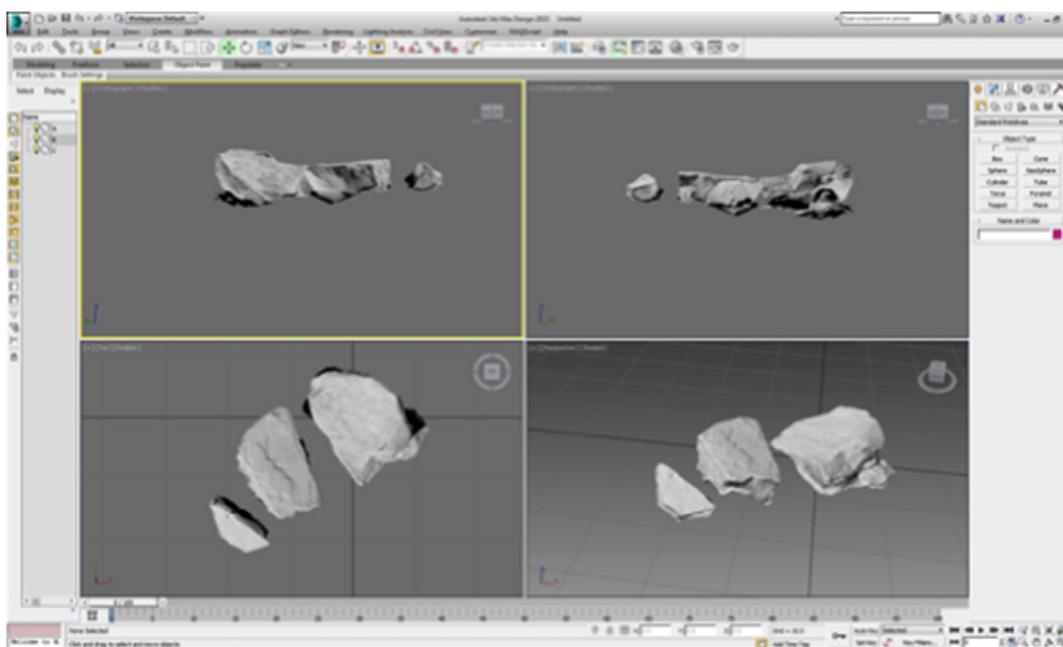


Fig. 13. 3D model of Monument 704 viewed in 3ds Max software: white clay mode.



Fig. 14. 3D model in 3ds Max: stills from animation showing transformation of original rock on left, transforming into 3-piece Monument 704 on right.

slight amount of texture, but not to the degree exhibited in the areas identified by the number 2. One could interpret then, that these gullies were formed by cutting away the sandstone and then leaving the new surface exposed to weather for a great period of time since there is some texture to the stone surface. There are no freshly cut, sharp edged surfaces visible on either stone. This supports the hypothesis that this working of the stone was ancient, as opposed to more recent. We know the gullies lead up to prominent knobs and notches at the top of the monument PB48, now concealed by the upper piece of stone in this digitized refitting. The gullies also flow down to areas on either side of the ridge. On the left side of the ridge, the gullies appear to give way to more irregular weathered rock face, which could be interpreted to be naturally occurring broken weathered face (see number 3). On the right side, the gullies appear to have been cut away in consistent arcs in a human-made manner (see letter C), bearing the texture of light weathering in a manner similar to the gullies above. Clearly, all of the stone surfaces, both what is interpreted to be natural and the anthropogenic sculpting work we observed, have been exposed to weather a very long time ago, since there is no fresh or sharp cut stone face visible.

Unfortunately, the digital re-assembly of Monument 704 into the original boulder from which all three parts were split, conceals all of the cupmarks and edge groove sculpting we observed along the top of the largest of the three stones. This work appears on the interior split face of the boulder. A flake scar remains visible along the seam, supporting our interpretation that the stones were split with Bronze Age technique, therefore dating the monuments (Cummins et al., 2015), but no other telltale evidence of human handwork is visible on the outside surface of the refitted assembly. All the evidence is positioned between the matched faces of rock.

The transformation of the final monuments from the original boulders was studied without disturbing the actual boulder monuments in any way, by animating digitally modeled components to simulate the original rocks before they were broken apart. Animations and composites of stills were composed to clearly explain this transformation. The use of *Project Memento* (Autodesk, 2014a) followed by *3ds Max Design* (Autodesk, 2014b) allowed high-resolution visualization to examine

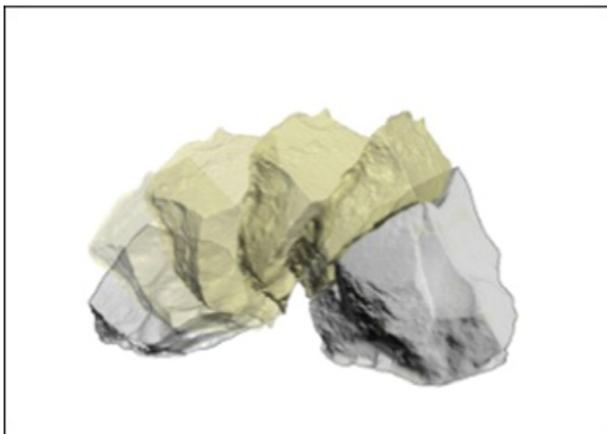


Fig. 15. Animation stills superimposed together to describe, in one image, transformation of original rock into PB48. The final positions are in gray tone.

and compare the matching surfaces of the Neolithic monument boulders. It was possible to see significant surface discrepancies beyond natural weathering on some of the pieces. Since all surfaces were exposed to the environment in a similar manner and should have similar weathering patterns, significant missing surface material on only one side of a matching pair was evidence of surface material being modified in some other manner. This evidence supports the hypothesis that these modified stones were worked by humans (Figs. 16 and 17).

Our investigation at the Cavan Burren site confirms that 3D digital technology can facilitate a fairly detailed, if not exact, analysis of boulder monuments (Burns and Nolan, unpublished) using methods similar to the 3D modeling used to record a sculpture (Bourke, 2012). Indeed, we easily documented existing conditions in a remote location without disturbing or even touching the original artifacts. The 3D models were virtually manipulated via animation with precision and studied in detail using open sourced software *Project Memento* followed by *3ds Max Design* (Autodesk, 2014a, 2014b). Autodesk's *Photo* and Agisoft's (2016) *Photoscan* could also be used for data capture; however, they require a subscription.

Project Memento (Autodesk, 2014a) is promoted as a streamlined “end-to-end solution for converting any captured reality input (photos or scans) into high definition 3D meshes” for various downstream workflows, including publishing and 3D printing.¹ We could take high-quality images in a range of 5 to 12 megapixels each, and use fewer images than other programs require. *Memento's* SfM basis for matching images (Jazayeri et al., 2010) simplifies data collection, because there is no need to attach targets on or near our artifacts to enable the software to stitch images together.

Although our software was easy to use and efficient, the subject matter and its context presented some challenges. The heavily forested background caused incongruities in *Memento's* (Autodesk, 2014a) image stitching (e.g., inconsistent focus produced spikes and holes in the stitched sequence that sometimes necessitated a reshoot of the entire artifact). In theory, one could patch in the missing parts with additional images, but only if exact lighting conditions could be replicated in an outdoor environment. To ensure consistent lighting and a complete mesh, Monument 704 required as many as four photography shoots.

Other challenges arose from the geometry and arrangement of the artifacts themselves (e.g., surfaces underground or too close to the ground could not be photographed). Also, the pieces of Monument 704 are spread over a 20' × 10' area, within which they are separated by trees. To capture the monument correctly, the camera was located at some distance from the assemblage, from whence it captured considerable background material that initially confused the software and complicated the stitching. Fortunately, although editing out the background information before processing the images with the *Memento* software can speed up the processing time, it ultimately does not affect the output (Autodesk, 2014a).

Despite its difficulties and limitations, photogrammetry is a viable and valuable tool to generate 3D records of sites as found, thus to preserve information that might otherwise be destroyed in the course of excavation (De Reu et al., 2013), or altered during restoration or preservation. In addition, it is a non-invasive means to test hypotheses, via static images and/or animation, while leaving the sites intact (Guidi et

¹ See <https://memento.autodesk.com/about>.

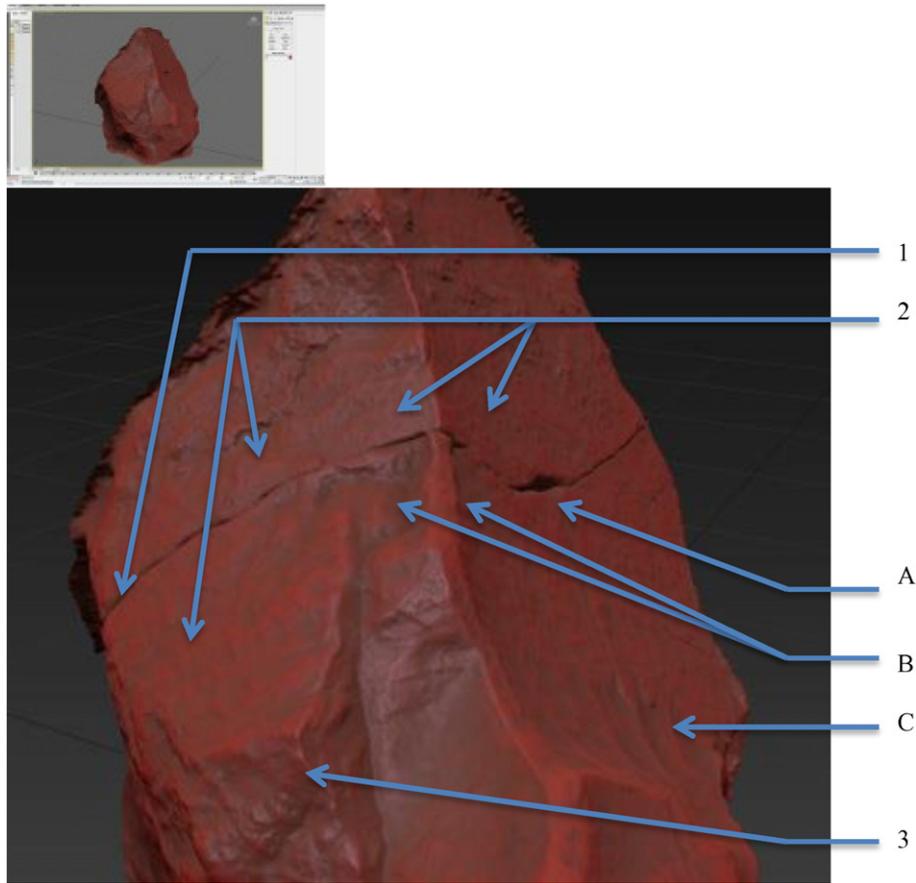


Fig. 16. 3D model of 2-piece Monument PB48 viewed in *3ds Max Design* software: red clay mode, enlarged. Evidence of human modifications are identified with letters. A indicates a percussion mark along the right side of the stone, a side effect of Stone Age stone splitting techniques. B and C indicate sculpting in the form of hollowed areas on both sides of the central ridge of the lower component. Naturally occurring actions on the stone are identified with numbers. 1 indicates the line of a fracture believed to have happened during the Bronze Age due to the percussion mark noted by A. 2 indicates original weathered face of stone. 3 indicates a naturally occurring break in the rock, cutting across its ‘bedding grain,’ the surface exhibiting a similar amount of weathering to original weathered face of stone noted by 2.

al., 2009). As digital technologies advance and their application becomes easier, these techniques will likely become even more efficient and economical to deploy in the field (Chandler et al., 2007). In addition, such technology will become more accessible to heritage specialists (Spring and Peters, 2014) and the relatively simple instrumentation can also be used by the public sector to help care for these sites, possibly increasing public concern for them, as well (Chandler et al., 2007; McCarthy, 2014).

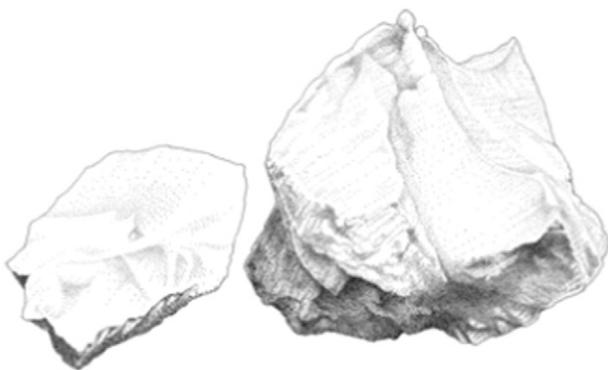


Fig. 17. Traditional Rock-Art stippled drawing of 2-piece Monument PB48 in situ, exhibiting sculpting (by Robin Ann Johnson ©2015).

Neolithic artifacts often go unappreciated: in County Fermanagh alone, over three dozen informally documented megaliths have been lost or demolished, their sites impossible for the Northern Ireland Environment Agency to classify with reasonable certainty (Foley and McHugh, 2014). Significant Neolithic stone arrangements are often found by chance. For example, Newgrange, a short drive from Dublin and arguably Western Europe’s finest example of a passage tomb, was discovered in 1699 by laborers seeking building materials (O’Kelly, 1983). Even distinguished 20th century archeologists have not necessarily comprehended sites for all their complexities. Had O’Kelly (1983) had 3D digital technology to confirm quantity and scale of materials and test his interpretation of the revetment wall above the kerb stones in advance of his 1960 “reconstruction” of Newgrange, the outcome would certainly have been different. Demonstrating the background research behind a proposed reconstruction was not part of the process at that time (Stout and Stout, 2008), nor was it practical. Fortunately, 21st-century, digital technology allows researchers with ordinary technical skills and equipment to make assessments of potential artifacts that are rapid, accurate, revealing, and easily presented to others (Chandler et al., 2007; Miles et al., 2014). These assessments, in turn, allow preservation authorities to make informed decisions and take appropriate precautions to secure and maintain valuable sites.

The results of Burns and Nolan’s surveys and our photogrammetry support the hypothesis that the boulder shaping is the result of something other than weathering, and quite possibly of purposive human activity. Both PB48 and 704 exhibit what appears to be sculpting. PB48 has

an elongated rounded ridge with gullies on both sides, which lead up to prominent knobs and notches at the top of the boulder. At least six other boulders in the Cavan Burren, one of which is almost identical to PB48,² exhibit similar knobs and notches. Burns and Nolan (unpublished) have recorded 60 examples of sculpting and categorized them by shape and effect.³ Although it seems, therefore, that Cavan Burren deserves further study, it currently remains unprotected. Its monuments remain vulnerable to damage from tree harvesting, the forces of trees felled by violent weather, upheavals and subsidence from growing roots and tree-trunks, as well as burrowing animals. Most of all, the site is vulnerable to human interference. The EGN system is an overlay designation that leaves ownership of parcels within it intact without limitations to the land use (e.g., hydraulic fracturing is not precluded in a geopark). Therefore it is important this valuable site be preserved (Burns and Nolan, 2011; Cummings et al., 2015; Foley and McHugh, 2014; Gunn, 2009; Kytmanow et al., 2008) and thoroughly photogrammetrically recorded for future research, perhaps with the added bonus of increased public participation and awareness of the archaeological heritage (McCarthy, 2014).

4. Conclusion

Scholars continue to explore the numerous benefits of incorporating multi-image photogrammetry into their archaeological research, from large-scale terrain modeling (Guidi et al., 2009) to smaller-scale analyses of rock art/inscriptions (Chandler et al., 2005; Spring and Peters, 2014), stone tools (Clarkson et al., 2014) and terra cotta figures (Bevan et al., 2014). Our study of two boulder monuments in a UNESCO Global Geopark involved non-invasively testing the hypothesis, through the use of multi-image photogrammetry and animation techniques, that the boulders show evidence of human sculpting. Using a consumer-grade camera along with *Project Memento* (Autodesk, 2014a) and *3ds Max Design* (Autodesk, 2014b) software, we were able to produce 3D images of the monuments and digitally animate the fit of adjacent boulder pieces onto the monument surfaces without disturbing the actual artifacts, ultimately providing evidence of human action on the boulders.

Further investigations can be made both in modeling and determining an exact fit of the stones, as suggested by researchers modeling the contact surfaces for small museum pieces (Bujakiewicz et al., 2006). It would be desirable to examine the fit and, in our case, see the volume of stone sculpted away but concealed from view in the digital re-fitting of parts. Solid models could be observed and hand fitted if the digital mesh models were sent to a 3D printer. One idea to help us examine the hidden parts of the matching pieces would be to insert a pliable material with 'memory' between the matching pieces so the negative space between them could be examined as a positive element once the matching pieces were taken apart. In areas of frequent contact, the material would be thin; in areas of sculpting, the amount of material would be great. A similar idea, in a digital medium, would be digitally 'filling' the intermediate space between the digitally re-fitted pieces and 3D printing or digitally observing this space as a positive element. Another idea furthering digital methods would be cutting digital sectional views through the refitted assembly, not unlike the sectional views digitally taken through living materials by MRI equipment or CAT scans. Certainly, any improvements in understanding a good fit between matching pieces of artifacts, or establishing a protocol for what defines an acceptable percentage-frequency of contact points to establish a 'fit', would be useful for digitally fitting fragile, finely scaled objects, extremely large objects, objects of unconfirmed significance, and objects of great importance. Establishing a similar protocol to quantify what is a pattern match in multiple artifacts of similar form would also be useful. Clearly, there is

tremendous potential in using digital tools to noninvasively demonstrate theoretical archaeological understanding in a format that can be made widely available.

Acknowledgements

This work was supported with a grant from Andrews University (Michigan, USA) (11-2011-xxxx-75-201141), (11-2011-9794-75-201010) and encouragement and assistance from the Marble Arch Caves Geopark and Foinsé Research. Many thanks to Heidi Massa, Jane P. Sheldon, Mary Ellen Newport, Gaby Burns and Jim Nolan for corrections and linguistic editing.

References

- Adobe Systems, 2015. *Adobe Photoshop CC*. CA, San Jose.
- Agisoft, 2016. *Photoscan*. St. Petersburg, Russia.
- Autodesk, 1999. *3D Studio Max*. Autodesk, Inc.
- Autodesk, 2014a. *Autodesk Memento beta*. Retrieved September 2015 from <https://memento.autodesk.com/about>.
- Autodesk, 2014b. In: Autodesk, Inc. (Ed.), *3ds Max Design*.
- Autodesk, 2014c. *Learn how to use 123d Catch*. Retrieved September 2015 from <http://www.123dapp.com/howto/catch>.
- Autodesk Laboratories, 2010. Easily create 3D models from photographs with Autodesk's project Photofly. Retrieved May 12, 2016 from <https://news.autodesk.com/press-release/easily-create-3d-models-photographs-autodesk-project-photofly>.
- Barazzetti, L., Binda, L., Scaroni, M., Taranto, P., 2011. Photogrammetric survey of complex geometries with low-cost software: application to the 'G1' temple in Myson, Vietnam. *J. Cult. Herit.* 12, 253–262. <http://dx.doi.org/10.1016/j.culher.2010.12.004>.
- Bevan, A., Li, X., Martinon-Torres, M., Green, S., Xia, Y., 2014. Computer vision: archaeological classification and China's terracotta warriors. *J. Archaeol. Sci.* 49, 249–254. <http://dx.doi.org/10.1016/j.jas.2014.05.014>.
- Bourke, P., 2012. Automatic 3D reconstruction: an exploration of the state of the art. *GSTF J. Comput.* 2, 71–75.
- Bujakiewicz, A., Kowalczyk, M., Podlasiak, P., Zawieska, D., 2006. 3D reconstruction and modelling of the contact surfaces for the archaeological small museum pieces. *Int. Arch. Photogramm. Remote Sens.* XXXVI 56–61.
- Burns, G., Nolan, J., 2007a. Prehistoric rock art in the Burren/Marlbank area. *Archaeology Ireland*. 21, 265–30.
- Burns, G., Nolan, J., 2007b. The Burren Marlbank: a report on recent discoveries in north-west Cavan and southwest Fermanagh. Accessed September 2015 from <http://cavanburren.ie> (website).
- Burns, G., Nolan, J., 2012. *personal communication*.
- Burns, G., Nolan, J., 2014. *personal communication*.
- Burns, G., Nolan, J., 2011. Burren megalithic forest park: some suggestions on the preservation, re-creations and presentation of a prehistoric karst landscape. Accessed September 2015 from <http://cavanburren.ie> website.
- Burns, G., Nolan, J., 2016. Burren-Marlbank, a prehistoric monumental landscape. *Blacklion: Marble Arch Caves Global Geopark* unpublished.
- Chandler, J., Fryer, J., 2013. January/February. Autodesk 123D Catch: how accurate is it? *Geomatics World* 28–30.
- Chandler, J.H., Bryan, P., Fryer, J.G., 2005. Non-invasive three-dimensional recording of aboriginal rock art using cost-effective digital photogrammetry. *Rock Art Res.* 22, 119–130.
- Chandler, J.H., Bryan, P., Fryer, J.G., 2007. The development and application of a simple methodology for recording rock art using consumer-grade digital cameras. *Photogramm. Rec.* 22, 10–21. <http://dx.doi.org/10.1111/j.1477-9730.2007.00414.x>.
- Clarkson, C., Shipton, C., Weisler, M., 2014. Determining the reduction sequence of Hawaiian quadrangular adzes using 3D approaches: a case study from Molokai. *J. Archaeol. Sci.* 49, 361–371. <http://dx.doi.org/10.1016/j.jas.2014.05.031>.
- Cummings, V., Moore, S., Richards, C., 2015. *Excavations of the Cleaven Carraig, CV004-059. Cavan Burren, Co. Cavan*.
- De Reu, J., Plets, G., Verhoeven, G., De Smedt, P., Bats, M., Cherretté, B., De Maeyer, W., Deconynck, J., Herremans, D., Laloo, P., Van Meirvenne, M., De Clercq, W., 2013. Towards a three-dimensional cost-effective registration of the archaeological heritage. *J. Archaeol. Sci.* 40, 1108–1121. <http://dx.doi.org/10.1016/j.jas.2012.08.040>.
- Foley, C., McHugh, R., 2014. *An Archaeological Survey of County Fermanagh: Prehistoric Period. vol. 1, part 1. The Northern Ireland Environment Agency*.
- Guidi, G., Remondino, R., Russo, R., Menna, F., Rizzi, A., Ercoli, S., 2009. A multi-resolution methodology for the 3D modeling of large and complex archaeological areas. *Int. J. Archit. Comput.* 1, 39–55.
- Gunn, J., 2009. Marble Arch Caves Global Geopark: earth science without borders! *Earth Herit.* 31, 20–22.
- Jazayeri, I., Fraser, C.S., Cronk, S., 2010. Automated 3D object reconstruction via multi-image close-range photogrammetry. *Int. Arch. Photogramm. Remote Sens.* 33, 305–310.
- Kytmanow, T., Mens, E., Kerdival, G., Gunn, J., 2008. Creating sacred and secular spaces: a study of the glacial erratics and early human settlement in the Cavan Burren landscape. *Cavan County Council Report*.
- Lemon, K., 2010. *Our Outdoor Classroom: A Teaching Resource Guide to the Marble Arch Caves Global Geopark. Marble Arch Caves Geopark*.

² Burns and Nolan (personal communication, 2014) demonstrated the similarity between this boulder and PB48 with plaster casts of the sculpted parts.

³ Since we shared with them our refined digital recording techniques, Burns has used photogrammetry to evaluate over 140 boulder arrangements.

- McCarthy, J., 2014. Multi-image photogrammetry as a practical tool for cultural heritage survey and community engagement. *J. Archaeol. Sci.* 43, 175–185.
- McCarthy, J., Benjamin, J., 2014. Multi-image photogrammetry for underwater archaeological site recording: an accessible, diver-based approach. *J. Marit. Archaeol.* 9, 95–114. <http://dx.doi.org/10.1007/s11457-014-9127-7>.
- Mens, E., 2008. Refitting megaliths in western France. *Antiquity* 82, 25–36. <http://dx.doi.org/10.1017/S0003598X00096411>.
- Miles, J., Pitts, M., Hembo, P., Graeme, E., 2014. New applications of photogrammetry and reflectance transformation imaging to an Easter Island statue. *Antiquity* 88, 596–605. <http://dx.doi.org/10.1017/S0003598X00101206>.
- O'Kelly, M.J., 1983. *Newgrange: Art, Archaeology and Legend*. Thames & Hudson, London.
- Parke, M., Meehan, R., Gallagher, V., Gately, S., 2013. The geological heritage of Cavan: an audit of county geological sites in Cavan. Retrieved from <https://www.gsi.ie/NR/rdonlyres/E4297C71-FE53-4E2D-BC12-B4213AF7C0FB/0/CavanCGSPart1.pdf>.
- Remondino, F., El-Hakim, S., Baltsavias, E., Picard, M., Grammatikopoulos, L., 2008. Image-based 3D modeling of the Erechtheion, Acropolis of Athens. *Int. Arch. Photogramm. Remote. Sens. Spat. Inf. Sci.* 37, 1083–1092.
- Spring, A.P., Peters, C., 2014. Developing a low cost 3D imaging solution for inscribed stone surface analysis. *J. Archaeol. Sci.* 52, 97–107. <http://dx.doi.org/10.1016/j.jas.2014.08.017>.
- Stanbury, P., Clegg, J., 1990. *A Field Guide to Aboriginal Rock Engravings*. Sydney University Press, Melbourne.
- Stout, G., Stout, M., 2008. *Newgrange*. Cork University Press.