RESEARCH REPORT SERIES no. 32-2012

STONEHENGE LASER SCAN: ARCHAEOLOGICAL ANALYSIS REPORT

ENGLISH HERITAGE PROJECT 6457

Marcus Abbott and Hugo Anderson-Whymark, with contributions from Dave Aspden, Anna Badcock, Tudur Davies, Mags Felter, Rob Ixer, Mike Parker Pearson and Colin Richards

ArcHeritage

ENGLISH HERITAGE

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NGR: SU 12244219

ISSN 2046-9799 (Print)

ISSN 2046-9802 (Online)

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SUMMARY

From May to August 2012, ArcHeritage, in collaboration with Dr Hugo Anderson-Whymark, undertook the archaeological analysis of laser scan data of Stonehenge, collected by the Greenhatch Group in March 2011.

The results of the project were beyond all expectations. The investigation identified traces of stone-working on virtually every stone, revealing significant new evidence for how Stonehenge was built. In addition, all of the known prehistoric carvings were identified and examined, and numerous new carvings of axe-heads and a possible dagger were revealed. The number of prehistoric axe-head carvings on Stonehenge has increased from 44 to 115; this doubles the number of Early Bronze Age axe-head carvings known in Britain.

Differences in patterns of tooling across Stonehenge were also identified that reveal significant new evidence for how, and potentially when, different elements of the monument were constructed. The analysis revealed that the Sarsen Circle was built and dressed with an apparent emphasis on the NE-SW solstitial axis. The study also presents new evidence allowing the question of the non-completion of the Sarsen Circle to be explored.

The project, funded by English Heritage, recorded all visible graffiti, damage, weathering and restoration. This revealed considerable evidence for the removal of stones from Stonehenge, and documented extensive damage from past visitors.

CONTRIBUTORS

Dave Aspden, Anna Badcock, Tudur Davies, Mags Felter, Rob Ixer, Mike Parker Pearson and Colin Richards

ACKNOWLEDGEMENTS

The project team thanks English Heritage for its support and co-operation during the project. Thanks also to the security team at Stonehenge who facilitated access to the monument during the field visits.

ARCHIVE LOCATION

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DATE OF RESEARCH

May - August 2012

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CONTENTS

LIST OF FIGURES

PART 1: THE PROJECT

Introduction

From May to August 2012, ArcHeritage, in conjunction with Hugo Anderson-Whymark, undertook an archaeological analysis of the stones at Stonehenge using laser-scan and photogrammetric data. This report documents the results of this analysis and provides new information about Stonehenge, in particular the methods of stone-working and monument construction, and the prehistoric and later carvings. These results demonstrate the importance of using laser-scanning technology for archaeological analysis and conservation management.

The digital analysis of the Stonehenge laser scan data set is a cutting edge project focused on maximising the potential for increased knowledge and understanding of this important monument. It utilises the data from the 3D laser scan survey commissioned by English Heritage in 2011 and conducted by Greenhatch Group. The digital data was collected at 0.5mm resolution across the entire stone circle, creating a remarkable data set that has enormous potential for new research. ArcHeritage were commissioned to visualise and analyse the digital data in a manner that both revealed and confirmed information about the stones; and to interpret any new discoveries in the wider context of the monument and its landscape. A secondary goal was to research and identify working methodologies that can be applied to the analysis of digital survey data, not only on Stonehenge, but also to a variety of chronologically and geographically diverse future heritage projects.

In total, 722 surface features were identified and recorded on the stones of Stonehenge. These features include areas of stone-working, prehistoric carvings, graffiti, damage, weathering and conservation.

Background

English Heritage is currently carrying out an analytical landscape investigation of the Stonehenge World Heritage Site (WHS). This includes a detailed metric survey of the standing stones and the landscape surrounding them known as 'the Triangle'. The survey of the stones carried out in March 2011 has produced 3D meshed models using laser-scan data from the metric survey. An initial assessment of these 3D models by Caroline Hardie of Archaeo-Environment Ltd has identified that the data has great potential for enabling new conclusions to be drawn on the stones of Stonehenge.

Report structure

This report is presented in four parts.

Part one (The Project) provides an introduction and description of the background to the project and conventions used in the report.

Part two (Visualisation and analytical techniques) Presents a discussion of the methods used to visualise and interrogate the laser scan data. It considers the strengths and weaknesses of different techniques and their applicability for examining different data sets.

Part three (Archaeological Analysis) provides the results of the archaeological analysis of the laser scan data. It presents the results in four sections that consider stone-working; prehistoric carvings; evidence for stone-breaking; and visitor damage, including graffiti and stone chipping.

Part four (Discussion) covers the implications the archaeological analysis has on interpretations of the monument.

Stone numbering

The numbering system used to identify individual components of the monument follows Petrie 1880 and subsequent modifications by Cleal *et al.* 1995. Where individual features (areas of stone-working, rock art, graffiti) are referred to in the text these are identified by a feature number (F). The feature number corresponds to that used in the Stone Biography and the accompanying database – to be published in the future. A plan of the structural elements and stones is shown on Figure 1.

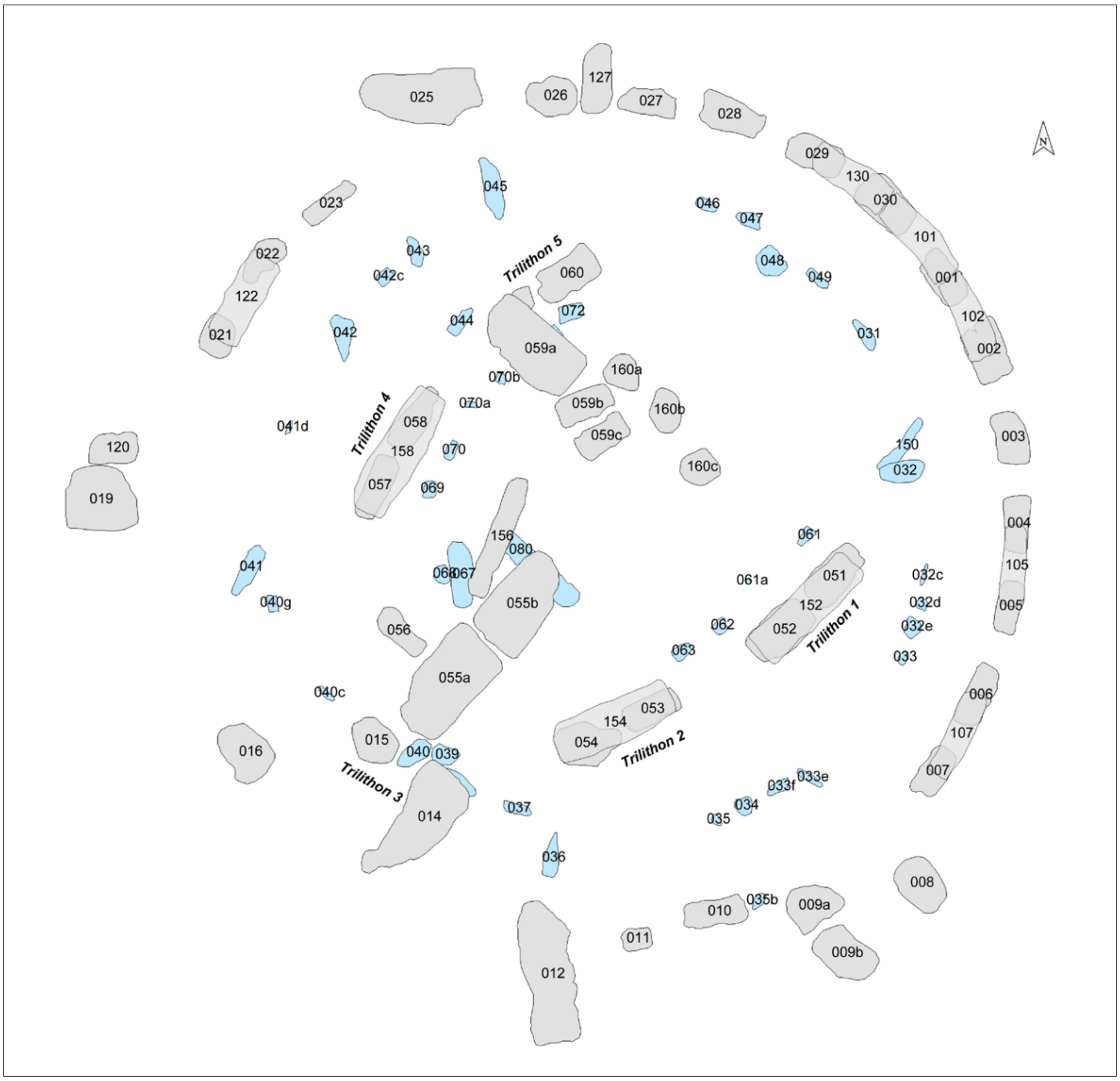

Figure 1. Plan of Stonehenge with stone numbers

PART 2: VISUALISATION AND ANALYTICAL TECHNIQUES

Methodological context

Currently, there are no published projects that compare to the scale of the Stonehenge laser scan analysis. While heritage projects have utilised sub-millimetre scan data, and other large monuments have been subject to high resolution survey, this project is the first attempt at applying high resolution survey to investigate a monument of this size and importance. The presence of dedicated analytical objectivesalso separates this project from possible analogues. A primary objective of this research is to gain new knowledge about Stonehenge through analysis of the survey data sets, unlike previous heritage surveys which focus on data capture rather than data analysis. The final defining characteristic of this project is the variance in technologies and methodologies utilised. The use of both laser scan and photogrammetric data collection created different data formats that could be analysed in different ways, providing opportunities for comparison between the data sets and numerous options for visualising the surface of the stones.

This section describes the methods utilised to analyse the survey data provided by English Heritage and attempts to layout a potential methodology for future projects. The unique nature of this project meant that innovative and often creative techniques were required for meaningful visualisation of the stones. Many techniques exist which are suitable for the visualisation of digital survey data, but each of these methods is linked to one type of data and is not transferable. ArcHeritage's task was to create a series of techniques which when applied to differing data sets would complement each other to produce coherent and comparable results. These techniques were developed through the enhancement of existing methods and the creation of completely new methods, the details of which are explained below.

Methods of analysis and visualisation results

Three bodies of digital data were supplied for the project by English Heritage: 1) laser scan survey data in the form of point clouds; 2) a 1mm resolution mesh model for every stone; and 3) 0.5mm mesh resolution for four stone surfaces. All of the data sets were generated by Greenhatch Group and totalled 850GB. Our initial analysis focused on the 1mm mesh data, which provided a complete record of every stone. We created a fourth, photogrammetric data set during our on-site visits.

The computer hardware used to examine all of the data was a Dell Precision T5500 with 36GB of RAM an Intel Xeon X5675 six core processor with Dual ATI Fire-pro V7900 graphics cards in a crossfire configuration.

Visualising the stones in a 3D environment

The first step in visualising any of the data sets required the creation of a visual template to which additional information could later be added. A basic visual catalogue of the stones was created from the 1mm mesh, providing a reference image of each individual stone that could later be plotted with features and carvings, creating an atlas of the monument. To create a template for each stone, the 1mm mesh data for that stone was individually loaded into Cinema 4D R13. On import the 1mm mesh was loaded into a null object which contains a predefined animation sequence. This animation creates five orthorectified high definition views of the mesh that correspond to the faces and top of the stone. High Dynamic Range filtering was applied to the images to define surface details.

Examining the 1mm mesh data

The analysis of the 1mm mesh data was conducted in a virtual environment whose function is akin to scientific visualisation, using sophisticated computer graphics to glean insight into the archaeology of the stones. On site the stones have several texture and surface variations which camouflage subtle features; however in the 3D environment we can strip off the texture, creating a uniformly coloured digital surface. We then create and apply new surface textures that enhance the archaeological features and minimize the influence of surface noise.

The digital visualisation environment was optimised for the examination and analysis of the 3D data set. Each mesh was loaded into Cinema 4D R13 and examined in real time as a whole object rather than a series of faces; complete Trilithons and uprights with lintels could be visualised together in context. We experimented with different textures, lighting techniques, and shadow decay values to define the combination that best allowed for the identification of surface features on the stones. We found a key benefit to real time visualisation was the flexibility and the interactive control of the position of the light source and camera. We discovered that the camera viewing angle (the point from which the stone is viewed) was equally as important as the lighting position and texture attributes. Some features were only clearly defined from specific camera angles and in conjunction with specific lighting setups. Also crucial to the visualisation of some features was the ability of the mesh model to be manipulated in real-time without any loss of quality. We examined every stone at full 1mm resolution with no mesh decimation. This manner of viewing each object was extremely advantageous in identifying the subtle evidence for tooling and surface dressing. Areas of archaeological interest were given unique feature numbers and descriptions before being plotted onto the orthographic images created for the stone catalogue. Lastly, the use of stereoscopic projection (3D visualisation on the computer monitor) was evaluated and found to be of little benefit to the identification of subtle surface features.

Results of examination of the 1mm mesh data

The techniques used to examine the 1mm mesh data proved extremely valuable and provided the project with a vast array of data, including a full set of previously unknown metrics relating to surface area, volumes and weight above ground. Surface features were visualised, identified and distinguished. These included different types and areas of stone working; areas of flaking; longitudinal and horizontal tooling; fine and coarse surface finishes; construction elements; and patterns of weathering, damage and erosion. In some areas we were able to detect layers of stone working and identify different stages of prehistoric working on the stone faces. Prehistoric rock art was also visible in this data set. Individual unique carvings were identified, but there was also a data signature, which seemed to indicate additional areas of shallow carving. The data signature appeared as an area of non-regular patterning that was almost reminiscent of a hammered sheet of metal – later enhancement would reveal this signature to be areas of extensive rock art.

The 1mm mesh data does not display all known features with clarity; incised graffiti was very difficult to identify. However, the rock art discoveries made from laser scan data in 2002/3 by Tom Goskar and colleagues from Wessex Archaeology/Archaeoptics were visible in the 1mm mesh; confirming that the resolution of the 1mm meshes was sufficient to display these important previous discoveries. Whilst the presence of the 2003 features was an encouraging result for the potential identification of new features in the 1mm mesh, the strange data signature suggested that with higher resolution data and enhancement more discoveries might be made.

Overall the 1mm mesh data appears valuable for identifying different stone working techniques, and it displays most of the known prehistoric carvings, but because of the mesh's limitations in displaying known features in total clarity, it did not prove suitable for the enhanced study of rock art. A simple comparison between the 1mm data and a sample of the 0.5mm data for Stone 53 revealed that the sub-millimetre data set was superior for the identification of rock art.

Examining the 0.5mm mesh data

Analysis of the 0.5mm mesh data was aimed at effectively visualising finer variations and carving on the stones' surfaces, starting with known areas of rock art on Stones 5 and 53. Examination of the high-resolution mesh data focused on controlling the interplay of light and shadow, a well documented method for highlighting surface variations that has been used successfully on numerous heritage projects, some examples of which are detailed in the *Multi Light Imaging Technique(s) for Heritage Applications* (Duffy in press) guide due to be published by English Heritage. We also referred to recent advancements in the use of reflectance imaging, and Hewlett-Packard's development of Polynomial Texture Mapping (PTM) provided proven methodologies for data analysis and enhancement.

Analysis of the 0.5mm mesh was conducted in a virtual environment created in Cinema 4D R13, consisting of 280 lights positioned in a hemispheric pattern about a single point of origin. The selected 0.5mm mesh was centred on this point. A single parallel camera positioned directly above the mesh rendered out a high definition image lit by one of the 280 lights. The light is then extinguished and a new light source is engaged, and the image is rendered again from the same camera position. The pitch and azimuth of the new light are different from the previous and therefore cast different shadows across the 3D surface. Using an animation, the process is repeated with all 280 light sources to produce a series of images. The suite of images are mathematically synthesised into a PTM file that allows the user to choose the direction of the light source and interactively re-light the surface of the stones. The changing interplay of light and shadow reveals fine details in the surface of the 3D mesh, which appear and disappear as the light passes over.

Results of examination of the 0.5mm mesh data

The creation, manipulation and analysis of the PTM files revealed previously unrecorded rock art on both Stones 4 and 53. The interplay of light and shadow on the mesh surface made it possible to discern individual carvings and indicated other areas of shallow carving. The nature of the stone surfaces made it difficult to define the exact shape of some shallow carvings; the edges of shadows are displaced by the surface texture on

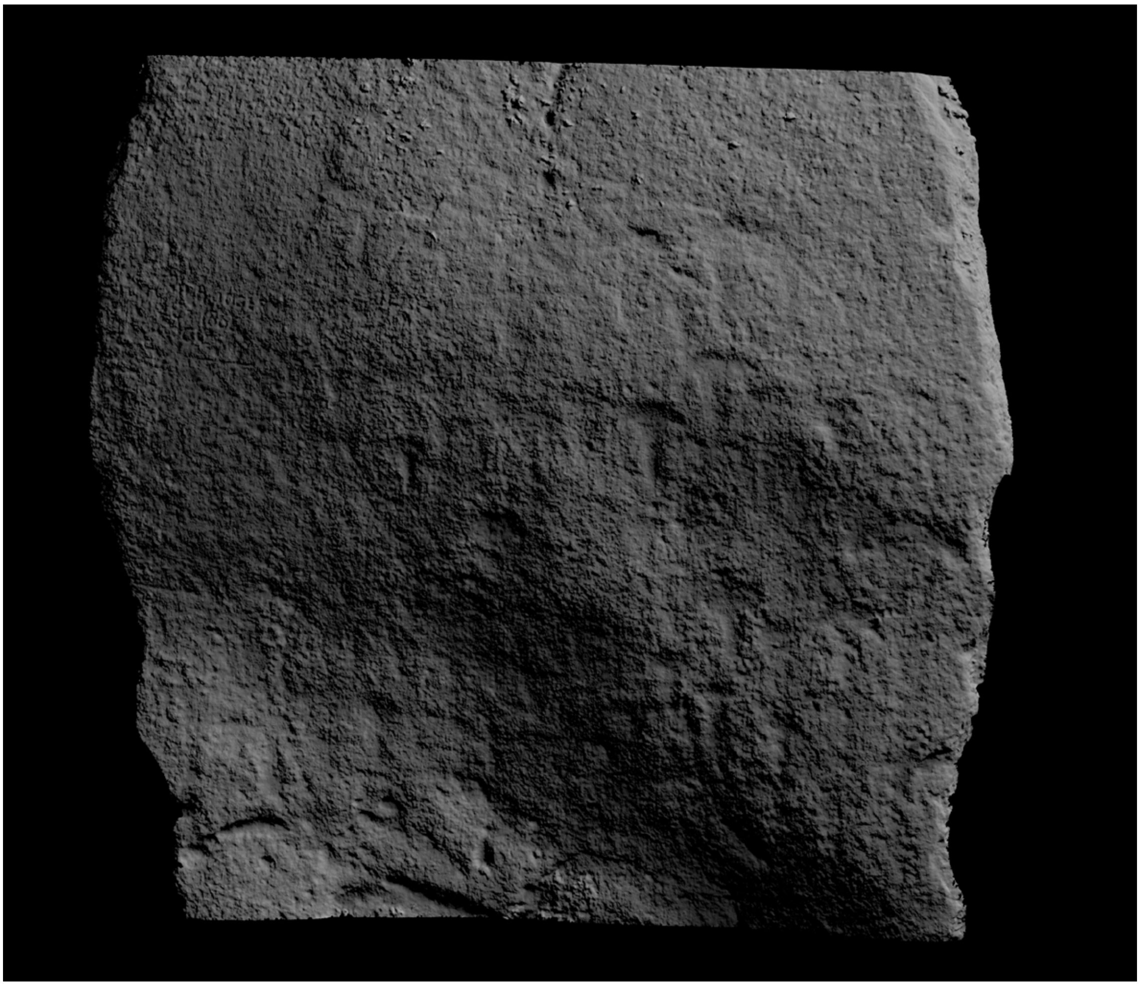

Figure 2. PTM, example sequence of shadows cast on Stone 4

which they are cast, making it almost impossible to define the exact edges of the most subtle carvings. Nevertheless we were able to identify numerous previously unknown features forming panels of rock art which extend beyond what had previously been recorded, and we were able to outline the edges of some known and newly discovered deeper carvings. Again, as in the 1mm mesh data, the same data signature mentioned above seemed to refer to very shallow carvings in large numbers forming potential panels or areas of rock art.

PTM files and the 1mm mesh data

After success with the 0.5mm mesh data, we experimented with creating PTM files for the 1mm mesh data, since PTM files might be a useful way of disseminating the data to the wider research community through empowering individuals with an inexpensive method of examining the 3D data. However, the PTM files of the 1mm mesh data were found to be inferior for the identification of stone working features when compared to real-time examination techniques. The fixed camera position necessary in PTM files hindered the visualisation of the form of the stones by treating each face individually. As already noted stone working features were sometimes best visualised from distinct oblique camera angles, and as a result would be difficult to identify in a PTM environment.

Examining the point cloud data

After the PTM files indicated that previously unrecorded rock art was visible in the survey data set, we focused on the original scan data in an attempt to clarify the outlines of newly discovered rock art and to enhance the shapes seen in the data signature. Investigation focused on areas of known rock art, including neighbouring stones, and any anomalies that were highlighted by other techniques. Within the point cloud data we used the individual XYZ files for each stone face and visualised them in Pointools using the plane shading function. To search for variations on the stone faces, a greyscale colour band was defined in relation to a fixed camera position and camera plane (a hypothetical plane perpendicular to the direction of the camera). Experiments determined that in order to identify stone surface features the optimum depth for the greyscale band was 75mm. This band was repeated to fill the entire space needed to visualise different contours of the stone. Each point in the XYZ file would be assigned a greyscale value based on its position within each band and its distance from the camera plane. These differences in greyscale values between neighbouring points reveal subtle changes in surface topography. The bands were moved through the point data at 1mm intervals; each point completes a full colour change from white to black in 75mm. Each 1mm movement was recorded using a parallel camera to create a high definition orthorectified image of the shaded greyscale pattern. These 75 images were rendered to form a complete animation of the sequence.

Figure 3. Greyscale 'plane shading' image of Stone 4

Results of examination of the point cloud data

The animation sequence clearly shows rock art features fading in and out of view as the greyscale band moves through the point cloud. The outlines of these features are clear and discernible; significant new rock art discoveries were made on Stones 4, 5, and 53 using this technique. We also examined Stones 6 and 54 which had clear negative results and no rock art was discovered. Because of the strong association between rock art signatures in the mesh data and the discovery of actual features in the point cloud data, we did not conduct an exhaustive investigation of the point data from all of the stones, but analysed all areas and associated regions that showed any indication of rock art in the mesh data. Overall, this analysis of the point cloud data was especially useful in our specific aim of identifying rock art, but when considering stone working it proved inferior to the techniques presented above.

Experimental convergent photogrammetry

During our site visits to Stonehenge we collected photogrammetric data of selected stone surfaces with the intention of creating high-resolution surface meshes in order to establish the resolution at which individual features become visible. The data was collected with a Leica V-LUX 2 Camera and was processed using Agisoft PhotoScan a convergent photogrammetric solution. The incisions of some graffiti on Stonehenge are less than 0.5mm across and are therefore not easily discernible in the laser scan data set which has a maximum 0.5mm resolution. We were able to process the photogrammetric data to produce mesh and point cloud data at a higher resolution than the scan data. Application of the PTM analysis technique described above and the Luminance Lensing method outlined below indicated that the existing Stonehenge data set could be enhanced in the future at a relatively low cost with the addition of higher resolution photogrammetric mesh panels. The results and analysis of the photogrammetric data also indicate that photogrammetry can be considered as an alternative data collection method for the stone surfaces at Stonehenge. The images and files of this experiment have been supplied to English Heritage as an additional component to this project.

Luminance Lensing

Luminance Lensing was a creative idea developed independently in-house specifically for analysis of the Stonehenge sub-millimetre meshes. The technique combines the best features of the real-time mesh visualisation and greyscale plane shading which are explained above. Luminance Lensing was applied to all mesh data types including photogrammetric and laser scan meshes. Also executed in Cinema 4D R13, Luminance Lensing uses a custom shader to adjust the luminance channel of a material which has been applied to a 3D mesh. The luminance value for each polygon is determined based on its relationship to a hypothetical intersecting 3D shape that acts like a virtual lens. The position of this 3D shape is fixed in relation to the viewing camera angle, much like the camera plane used in the plane shading technique. However, unlike the 2-D camera plane in the plane shading technique, this 3D shape is capable of interacting with the 3D mesh. The luminance value of each polygon can be 'focused' by moving the camera back and forth in relation to the mesh surface. Rock art features are revealed as areas of increasing or diminishing brightness as the camera pans across and in/out of the surface. Settings allow for both a positive and negative (much like the negative of a photograph) view of the 3D rock surface. There are two types of lens: a cylindrical prism which works well for linear features on flat surfaces, and a conventional convex circular lens that is better suited for examining irregular surfaces.

Rock art is visualised in real time on the 3D mesh. Once in focus, the texture can be 'baked' (locking the texture to the 3D surface) to a UV map, and the outlines of the carvings can be accurately plotted in relation to the rock surface. High definition renders can be made of the 'focused' area and then enhanced using a custom HDR imaging filter. The results of this technique produce clear and concise images of the features. These images are particularly useful, as they represent an objective visualisation of the data set and when presented alongside the interpretative drawings illustrate the process and foundation on which interpretations are based.

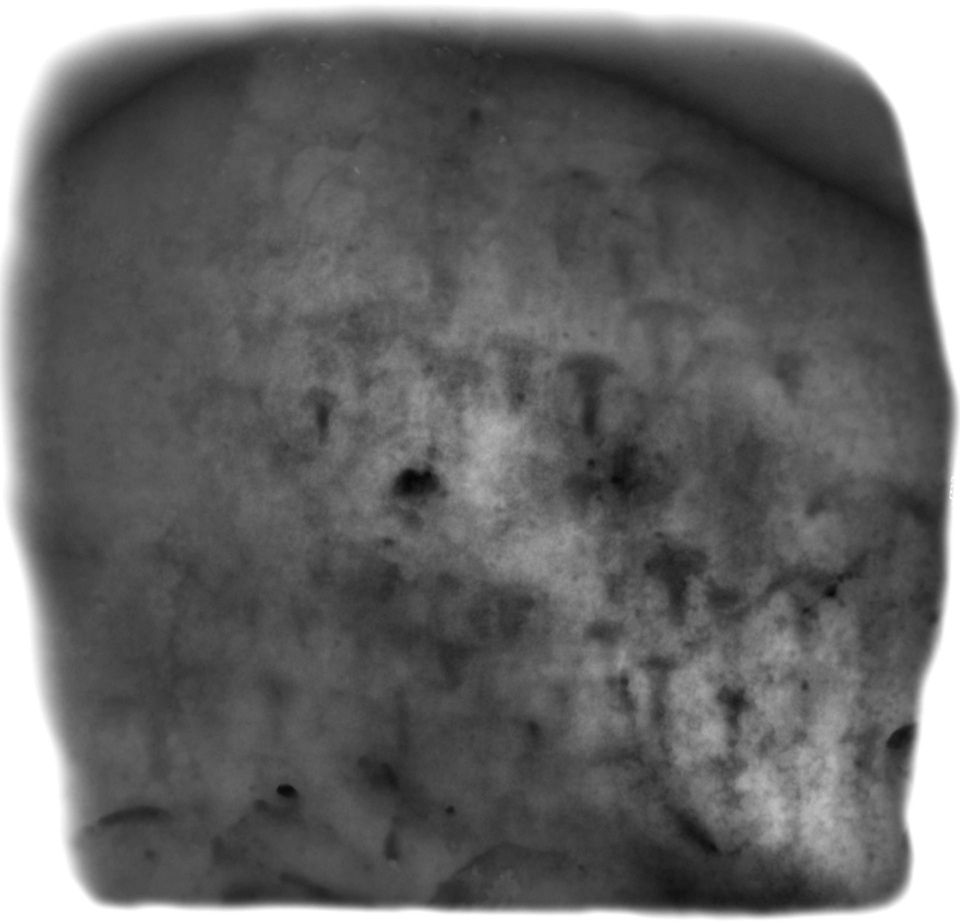

Figure 4. Luminance lens image of Stone 4

Experiments in the visualisation of surface normals

As part of our original project design we attempted the construction of a set of adaptive textures capable of visualising subtle surface differences within 3D meshes using surface normals. We used the surface normals from the 0.5mm mesh to colour polygons based on the orientation of the normal, a process which created a map of the 3D geometry of the mesh. We hoped that we could visually enhance this map image to highlight surface features. We edited the normal map in Photoshop to isolate colour channels that relate to incisions and variations on the stone surface. Through this technique we were able to produce an image that represents a specific range of normals. Prehistoric carvings are discernible within the image, but are not particularly well defined. Although visual enhancement of surface normal maps did not prove as effective as plane shading or Luminance Lensing in analysing the mesh data, further development may refine this technique. Nevertheless, normal visualisation offers a comparative and complementary set of results which can be combined with other techniques to enhance interpretations at Stonehenge.

The creation of normal maps can also be used to enhance decimated meshes with low polygon counts to appear at a higher resolution. Maps of the surface normals could therefore be distributed in conjunction with low resolution meshes to allow broader access to the 3D models; this combination of files reduces the computer processing power required to view a basic visualisation. Additionally, because they can be used to create 3D meshes of a surface, surface normal maps also provide an alternative method of storing and distributing 3D surface data, although some data loss may occur in the process.

Field visits

An initial field visit was undertaken by the project team on 7th March 2012 to examine previously reported areas of stone working, prehistoric carvings and various areas of graffiti and damage. On 19th May 2012, during the analysis, Hugo Anderson-Whymark undertook a site visit and, once the desk-based analysis was complete, a final visit was undertaken by the project team on 25th July 2012 to clarify and check results.

The field visits allowed patterns of stone working to be checked and in all cases interpretations were confirmed. The field visits also allowed areas of reduced laser scan coverage to be examined, for example the tops of stones in the Bluestone Horseshoe and the top of fallen Stone 19. Particular attention was paid to areas where vegetation masked the stone surfaces in the laser scans. This allowed the identification of a second tenon on the top of Stone 19 and fine pick dressing on the sides of Stone 45. All potential prehistoric carvings were examined on the ground and while the new axe-head carvings could not be seen various possible cup-marks were examined and confirmed as natural features.

PART 3: ARCHAEOLOGICAL ANALYSIS

Geological introduction to the stones at Stonehenge

The stones at Stonehenge are coarsely divided between the large sarsens (a hard, siliceous sedimentary rock rather like sandstone) and smaller 'bluestones' – a name that covers a variety of predominately igneous rocks of distant origin. Most of the 'bluestones' are spotted/unspotted dolerite, a medium-grained, basic igneous rock. Other 'bluestones' are rare but include a fine-grained, Devonian sandstone (the Altar Stone) and four acid to intermediate, fine-grained volcanics namely the rhyolites/rhyolitic tuffs and dacites (Ixer and Bevins 2011a, Bevins *et al.* 2012). Other bluestone rock types are reported only from buried stumps and these include sandstones and volcanic ashes (Thorpe *et al.* 1991).

The stones from which Stonehenge was built have long been known to have derived from sources distant from the site. The bluestones, other than the Altar Stone, are thought to derive from the Preseli Hills of southwest Wales over 200km away; however, petrological analysis has not been carried out on all of the bluestones and they may have originated over a wider area in southwest Wales.

Sarsen stones are available in the landscape immediately surrounding Stonehenge, but they are more numerous to the north in the Vale of Marlborough, and it is commonly speculated that they come from the latter region (*e.g.* Stone 1924; Atkinson 1956). Visual examination of the sarsen stones by the authors indicates that three or more distinctive types of sarsen have been used at Stonehenge, potentially indicating that the stones were obtained from multiple sources. Sarsens are also found across large areas of Wiltshire, Hampshire, Buckinghamshire and Kent; and it is possible that the stones originate from one or more of these areas.

The effects of surface weathering

The stones of Stonehenge have, in general, survived in a good state despite being weathered by the varied climate of Salisbury Plain for many millennia. Chemical weathering of all these lithics is slow, largely because of their high silica content. The sarsens are chemically inert (there is very little pyrite) but have joints and fractures that can invite enhanced weathering.

The effects of weathering are apparent, to varying degrees, on most exposed stone surfaces. The once fresh greyish-white surfaces of pick dressed sarsen have weathered to a dull grey, while the blue-grey surfaces of the dolerite bluestones have developed a dull brown weathered surface.

The dolerite bluestones have, however, fared well against chemical weathering and most of the dressed surfaces remain crisp and clear. Other bluestone lithologies, particularly the volcanics, have fared less well as they have a strong planar fabric that is susceptible to mechanical and chemical weathering. Notably, all stones of altered volcanic ash (four examples), sandstone with mica (two examples) and calcareous ash (one example) (lithologies given by Atkinson 1956) only survive as below ground stumps. Weathering may, in part, explain the denudation of these stones, but deliberate flaking and breakage (along with some stones of rhyolite and dolerite) may have further reduced these stones.

Chemical erosion by water has affected many of the sarsens, but it is clear that certain stones are more susceptible to weathering than others. In extreme cases, water has chemically eroded channels into the dressed stone surfaces (*e.g.* Lintel 152) and some exposed upper surfaces have almost weathered away (*e.g.* seats on Stones 5 and 6). Hollows and fissures in horizontal surfaces (*e.g.* the tops of lintels, or in hollows of the faces of fallen stones) have been eroded by pooled water.

Prof William Gowland (Gowland and Judd 1902) considered that surface weathering had removed virtually all traces of tooling above ground, and he highlighted the fresh coarse pecking visible on the below ground base of Stone 56 as evidence. His observations influenced both Stone (1924) and Atkinson (1956), who reiterated that most above ground traces of tooling had been lost, but the degree of weathering has been overstated as the coarse dressing observed by Gowland is only typical of the stone surfaces below-ground level, for example on the bases of Stones 55 and 59; above-ground surfaces are typically more finely pick dressed. This is not to say that traces of tooling on exposed above-ground surfaces have not weathered, as in many cases they are faint, but on virtually all surfaces traces of stone-working are still present.

The effects of surface lichen

The stones at Stonehenge are extensively covered by numerous species of lichen. Crustose species adhere tightly to the stones and occur from ground level upwards, while shrubby fruticose species are typically found above head height, as below this level they have been dislodged by visitors. Due to concerns that the lichen was masking areas of stone-working and prehistoric carvings, English Heritage commissioned CyArk to investigate digital methods of identifying and removing lichen from the laser scan data (Barton 2012). The techniques developed succeeded in identifying lichen but attempts to digitally 'remove' it were largely unsuccessful as they removed evidence for stone-working in addition to the lichen. As a result, the 3D models examined for this analysis included areas of lichen coverage.

The flat crustose species, although common, are discontinuous and typically only limited parts of large areas of stone-working were obscured. Moreover, as these species are comparatively flat their presence did not hinder the identification of any prehistoric carvings using PTM, Plane Shading or Luminance Lensing. The fruticose species presented a more significant problem as their shrubby form entirely obscures areas of the stone surface. However, fruticose lichen coverage was intermittent across large areas of the stones allowing areas of stone-working to be identified, although small *c.*40mm diameter areas were obscured. The digital signature of the fruticose lichen in the meshed 3D models was also very distinctive (they appeared as smooth domed or lumpy areas) and these were easily distinguished from areas of stone surface. Dense coverage of fruticose lichen however hindered examination of 23% (245 m^2) of the stones. It should however be noted that all graffiti and prehistoric carvings occur below the level that fruticose lichens are found, potentially indicating that these lichen will have only obscured areas
of stone-working.

Making Stonehenge: evidence for stone-working

Introduction

In total, 448 discrete areas of stone-working were recorded. All visible faces of the Bluestone Horseshoe, Sarsen Horseshoe and Sarsen Circle exhibit stone-working, with the exception of sides and back of Stone 14 and backs of Stones 15 and 16 in the Sarsen Circle. In contrast, only three of the thirty surviving stones in the Bluestone Circle are dressed. Among the outlying stones only the Slaughter Stone (95) is extensively dressed: minor dressing is present on Station Stone 93, while Station Stone 91 and the Heelstone (96) are not worked.

In many cases the dressed stones exhibit successive areas of stone-working revealing sequences of coarse to fine dressing. Coarse and very coarse dressing is then used for final fitting on the seats, tenons and rebates. Techniques of dressing vary between stones and structural elements, and a single *chaîne opératoire* cannot be constructed. The stone-working techniques for the sarsens and bluestones are therefore described separately. The techniques employed are then discussed in relation to the key structural elements of the monument.

Sarsen-working techniques

In the 1720s Stukeley recognised that many of the stone surfaces at Stonehenge were dressed (Stukeley 1740), but it was not until the 20th century that attempts were made to characterise patterns of stone-working and determine the methods employed. William Gowland (1902) and E. Herbert Stone (1924) provide valuable accounts, but Richard Atkinson (1956; 1960; 1979) provided the most comprehensive account, prior to this present study. Atkinson's terminology (*e.g.* coarse vertical tooling, fine transverse tooling and pick dressing) has been followed with minor amendments to his definitions and proposed stone-working sequences. The techniques employed across the monument are described below in broad sequential order, essentially the coarsest stone-working technique to the finest. But it must be born in mind that individual stones and faces have different sequences (*e.g.* in many cases the final fine pick dressing is applied directly over an unworked surface) and that certain techniques are only employed on selected areas of the monument (*e.g.* fine transverse tooling is exclusively used on sarsen and bluestone trilithons).

Splitting. Traces of three split sarsen surfaces survive within the Sarsen Circle; other examples may once have existed but will have been removed by later dressing techniques. It is not apparent what method was employed to split the sarsen stones, but Atkinson speculated that the stones may have been split using techniques employed by masons up until the 19th century. The first technique entails driving wooden wedges in cracks or pecked holes and soaking them in water until the wood expands and splits the stone, while the second technique involves heating the stone with fire and inducing a crack by pouring water on the surface and dashing the stone with heavy mauls (1956, 117-8). It is difficult to distinguish between these techniques from archaeological evidence. Example: Exterior N faces of Stones 27 and 28.

Large-scale flaking. Sarsen possesses a sub-conchoidal fracture pattern, as it is essentially silica sand cemented with silica; as such it can be flaked. Evidence that this technique was employed at Stonehenge is provided by the presence of a large sub-conchoidal flake scar on the outer face of Stone 3. This technique may also have been employed to dress the base of Stone 30, which appears to exhibit flake scars exceeding 1m in length (Pitts 2001, 216). Flaking appears to have been employed only at an early stage of dressing, associated with splitting the stone. Flaking on this scale would require an exceedingly heavy hammerstone, perhaps comparable to the largest *c.*30kg examples recovered from excavations. Example: exterior NE face of Stone 3.

Small-scale flaking. Six sides and one exterior face of the Sarsen Circle have been worked by flaking, and other examples may have been removed by later episodes of dressing. In general these flake removals are comparatively small (less than 0.30m) and appear to have been removed in sequences to produce square sides on the stones. This small-scale flaking may have been employed in conjunction with other coarse dressing techniques. Small-scale flaking may have been achieved by using indurated sarsen hammerstones of appropriate weight, probably of no more than a few kilograms for the smaller removals. Example: Stone 6 N side.

Coarse dressing, longitudinal ridges with transverse tooling. Distinctive parallel ridges on some stones measure *c.*20-30 cm wide and *c.*5-7.5 cm deep, containing bands of transverse tooling *c.*10 cm wide and *c.*1 cm deep. This technique often appears in conjunction with fine transverse tooling and, in places, the former may be a contemporary mode of dressing. Richard Atkinson proposed that the ridges created by this mode of dressing were removed by flaking using a large hammerstone, before finer dressing techniques were applied; no evidence for the removal of these ridges by flaking was recorded. This technique was only employed on the exterior faces of the Sarsen Horseshoe (Stones 52, 54, 58 and 59; a rib on the Stone 53 may also represent a relic of this technique), with the possible exception of a rib on the SW side of Stone 59a. This technique is likely to have been achieved using a heavy hammerstone, probably of 1-5kg in weight. Example: NW exterior face of Stone 59a.

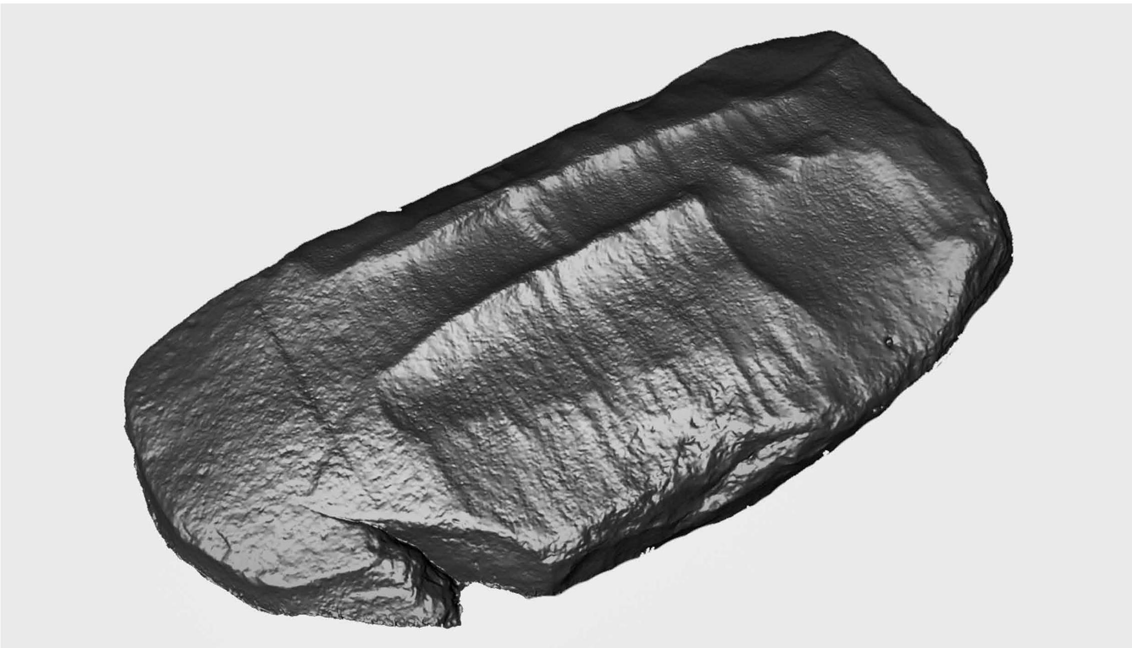

Figure 5. Coarse dressing, longitudinal ridges with transverse tooling on the exterior NW face of Stone 59a

Coarse dressing, longitudinal without ridges. This technique consists of broad, shallow and fluid, longitudinal channels that lack the prominent ridges and transverse tooling observed above. This technique was employed to remove prominent protrusions on the exterior faces of Stones 10 and 28 in the Sarsen Circle and on the exterior face of the Slaughter Stone (Stone 95). This technique is likely to have been achieved using a heavy hammerstone, probably of 1-5kg in weight. Example: SE exterior face of Stone 10.

Coarse dressing, other. This category comprises areas of coarse dressing that have not been worked in a specific orientation (*e.g.* longitudinal or transverse), for example, coarse dressing on the foot of Stone 55a, and facetted dressing at the top of the exterior N face of Stone 28. This technique is likely to have been achieved using a heavy hammerstone, probably of 1-5kg in weight.

Fine tooling, transverse. Small, shallow transverse grooves are visible, measuring 5-10 cm wide by *c.*20-30 cm long and *c.*5-20 mm deep (Figure 6). As previously noted, this mode of tooling often extends from, and may be broadly contemporary with, the coarse dressing with longitudinal ridges and transverse tooling. The coarsest forms of this dressing appear to be overlain by longitudinal fine tooling (*e.g.* NE face of Stone 60), but fine versions of the tooling exist, which are of comparable quality to the longitudinal fine tooling; however, in these cases no stratigraphic relationships can be determined. This style of tooling is found on all of the stones in the Sarsen Horseshoe, but it occurs only on one rebate on Lintel 122 in the Sarsen Circle. In many cases, this tooling is overlain by fine pick dressing and, in the majority of cases, virtually all traces of this mode of tooling have been removed. This tooling may have been created using handheld light to medium-weight hammerstones of *c.*0.5-2kg. Example: Stone 60 NW exterior face (comparatively coarse); Stone 54 SW side, towards base (fine).

Fine tooling, longitudinal. Small shallow longitudinal grooves are visible, measuring *c.*5-7.5 cm wide by *c.*20-30 cm long and *c.*5-15 mm deep (Figure 6). This tooling is typically slightly finer than the transverse fine tooling. On the Sarsen Horseshoe this style of dressing is found on the sides of Trilithons 1 and 5 (Stones 51, 52, 59 and 60) and one area was observed on Stone 53 (Trilithon 2). In the Sarsen Circle this dressing occurs on the sides of 17 uprights, 1 interior face (Stone 22) and 1 exterior face (Stone 30). This dressing was also recorded on Sarsen Circle Lintel 102 and on one side of the Slaughter Stone (Stone 95). This tooling may be created using a light to medium-weight hammerstone of *c.*0.5-2kg.

Figure 6. Fine longitudinal and fine transverse tooling on the NE side of Stone 60

Grinding to a high polish. Small areas (<0.30m across) ground to a high polish were observed in facets of the fine transverse tooling on the base of the SW side of Stone 52 and the fine longitudinal tooling on the NW side of Stone 16. On the former surface it was clear that the polished area was subsequently pick-dressed. It is unclear if these areas represent a distinct style of dressing, or if they indicate that the stones were used as *polisoirs* before they were erected.

Pick dressing, fine. This very fine pick-dressed (or pock-marked) finish was probably achieved by pounding with a small handheld hammerstone weighing less than 1kg. This dressing overlies all of the dressing techniques considered above, and numerous sarsen surfaces that show no other evidence of dressing. On the latter surfaces, this style of dressing reflects the removal of the original orange-brown or grey crust from the sarsen surface, revealing the fresh grey-white interior of the stone. Fine pick dressing was employed as the final visible surface finish on virtually every stone, although the degree to which it removed the earlier modes of dressing was variable. Example: interior SW Face of Stone 1.

Pick dressing, coarse. This is similar to fine pick dressing, but the 'pock marks' are much larger. This mode of dressing was predominately used to shape surfaces that were not visible once the monument was completed, such as seats and tenons on uprights belonging to the Sarsen Circle and Sarsen Horseshoe; and the tongue-and-groove joints on the lintels of the Sarsen Circle. In a few cases, coarse pick dressing was employed on visible faces, for example, the outer face of Stone 28, but these are uncommon. This style of dressing is likely to have been produced by a light to medium-weight handheld hammerstone. Example: tenons and seat on top of Stone 28.

Pick dressing, very coarse. This is an exceedingly rough-pecked or pick-dressed surface. This technique was predominately employed to produce rebates on the Sarsen Circle lintels, but it was also used to produce the tenon and seat on Stone 14 and limited areas are present on the sides of Stones 2 and 3. This tooling was primarily used for the expedient removal of stone during construction, *e.g.* to fit the lintels, and it can commonly be seen to truncate fine pick dressed surfaces on the underside of lintels. Where present on the sides of the stones, the surface was subsequently pick dressed, for example on the sides of Stones 2 and 3. It is unclear what tool was used to produce this surface, but it is possible that a heavy, pointed hammerstone may have been employed. Example: rebate on bottom of Lintel 102 (Figure 7).

Grinding/polishing. The only substantial areas of surface grinding are present on the lower *c.*2m of Stones 53 (interior NW face) and 10 (Interior NW face). The position of the grinding indicates that this surface finish is likely to have been applied to the stones after they were erected. The presence of this surface in association with the axe marks on Stone 53 may indicate that this surface finish was applied to selected areas in the Early Bronze Age. Example: lower *c.*2m of Stone 10 interior NW face.

Bluestone-working techniques

The bluestones exhibit a limited range of dressing techniques. The stones in the Bluestone Horseshoe, which have been re-used from an earlier structure that

Figure 7. Very coarse pick dressing on a rebate in Lintel 102. The rebate is the rectangular depressed area directly above the upright. (Photograph Hugo Anderson-Whymark)

Figure 8. Stone 59a NE side; Fine transverse tooling (bottom) and fine longitudinal tooling overlain by coarse pick dressing (left), which in turn is overlain by fine pick dressed surface (right). A fragment of stone is missing from the bottom left hand edge. (Photograph Hugo Anderson-Whymark)

incorporated spotted dolerite trilithons, exhibit a fine transverse tooling overlain by fine pick dressing. A similar pattern of dressing was observed on the lintels re-used as uprights in the Bluestone Circle. Coarse pick dressing is confined to a single face in the Bluestone Circle. These techniques are described below.

Fine tooling, transverse. These small, shallow longitudinal grooves measure *c.*5-7.5cm wide by *c.*20-30cm long and *c.*5-15mm deep. No traces of earlier coarse dressing, splitting or flaking were observed on the bluestones, but these techniques are unlikely to have been needed in most cases as the dolerite occurs in regular, natural joint blocks. Fine transverse tooling may, therefore, represent the coarsest technique employed to shape the stones. Example: exterior W face of Stone 69.

Pick dressing, coarse. This is similar to the fine pick dressing, but the 'pock marks' are much larger. This style of dressing was only observed on one face of Stone 45 in the Bluestone Circle. It was probably produced using a medium to heavy-weight hammerstone.

Pick dressing, fine. This very fine pick-dressed (or pock-marked) finish was probably achieved by pounding with a small handheld hammerstone weighing less than 1kg. This dressing overlies the fine transverse dressing and, in many cases (particularly on the interior face and stone sides), it virtually removes all traces of earlier dressing. Example: interior E face of Stone 69. Fine Pick dressing was also used to removed the tenons from the tops of Stones 67, 69, 70 and 72.

Patterns of stone-working at Stonehenge

The patterns of stone-working (Figure 9a and 9b) are described below in relation to the main structural components of Stonehenge.

Sarsen Horseshoe (Trilithons 1-5)

The Sarsen Horseshoe consists of five trilithons that graduate in height towards the Great Trilithon (Trilithon 3). The stones of the Sarsen Horseshoe are all present at Stonehenge, with the exception of small fragments of Stones 55, 59 and 160. Stones 55, 59 and 160 fell and broke into fragments at unknown dates, prior to the illustration of Stonehenge by Lucas de Heere in 1574, while Trilithon 4 (Stones 57, 58 and 158) fell outwards in 3rd January 1797, having been undermined by the digging of a hole by in 1796. The latter trilithon was re-erected by Richard Atkinson *et al.* in 1958. Trilithon 2 (Stones 53, 54 and 154) was leaning towards the centre of the monument and was straightened and set in concrete by Richard Atkinson in 1964.

The Sarsen Horseshoe exhibits a complex pattern of dressing that provides a degree of architectural unity to this aspect of the monument, but each trilithon has its own idiosyncrasies, which are explore further below. The regular increase in height from Trilithons 1 and 5 towards the Great Trilithon is remarkably consistent. It is also notable that the general form of Trilithons 1, 2, 4 and 5 is very similar: the external sides of the trilithons are essentially straight, while the gap between the stones is a pronounced 'V'-shape. In the Great Trilithon this pattern is reversed and the outer sides of the uprights are convex and the internal sides are perfectly straight. The narrow, exceptionally regular

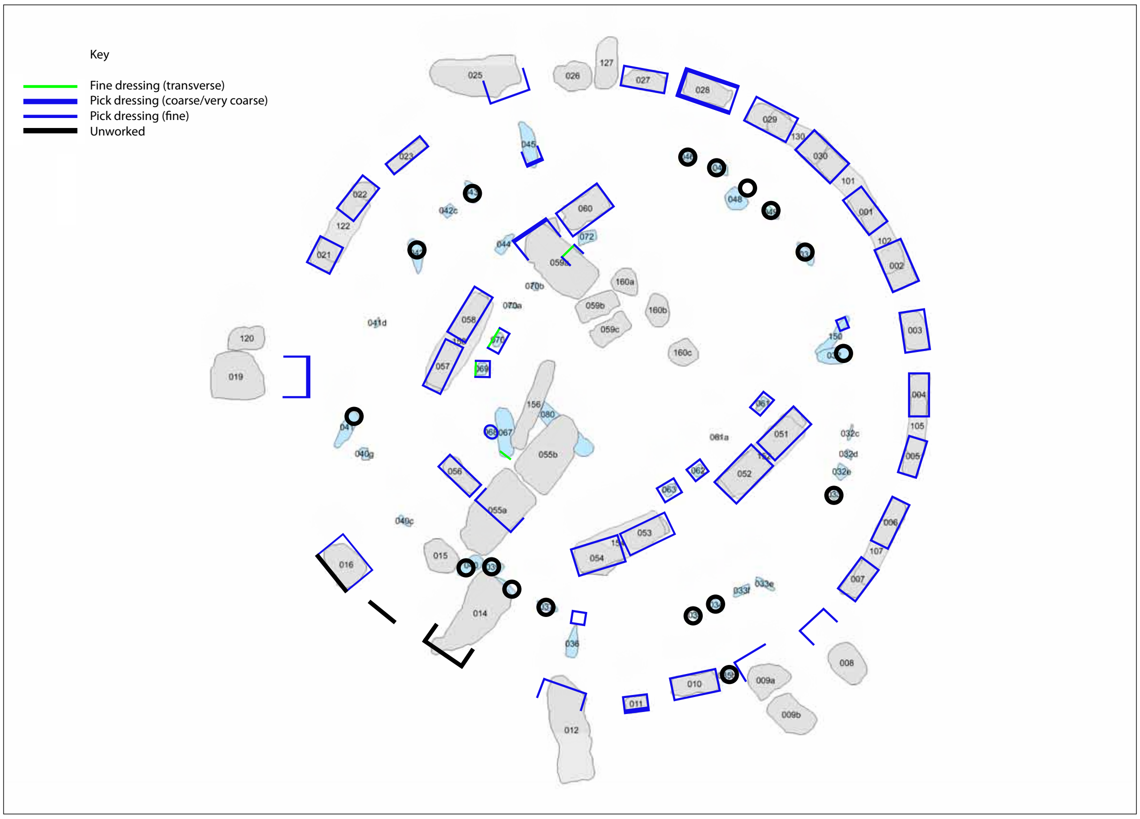

Figure 9a. Patterns of stone-working at Stonehenge: surface finishes

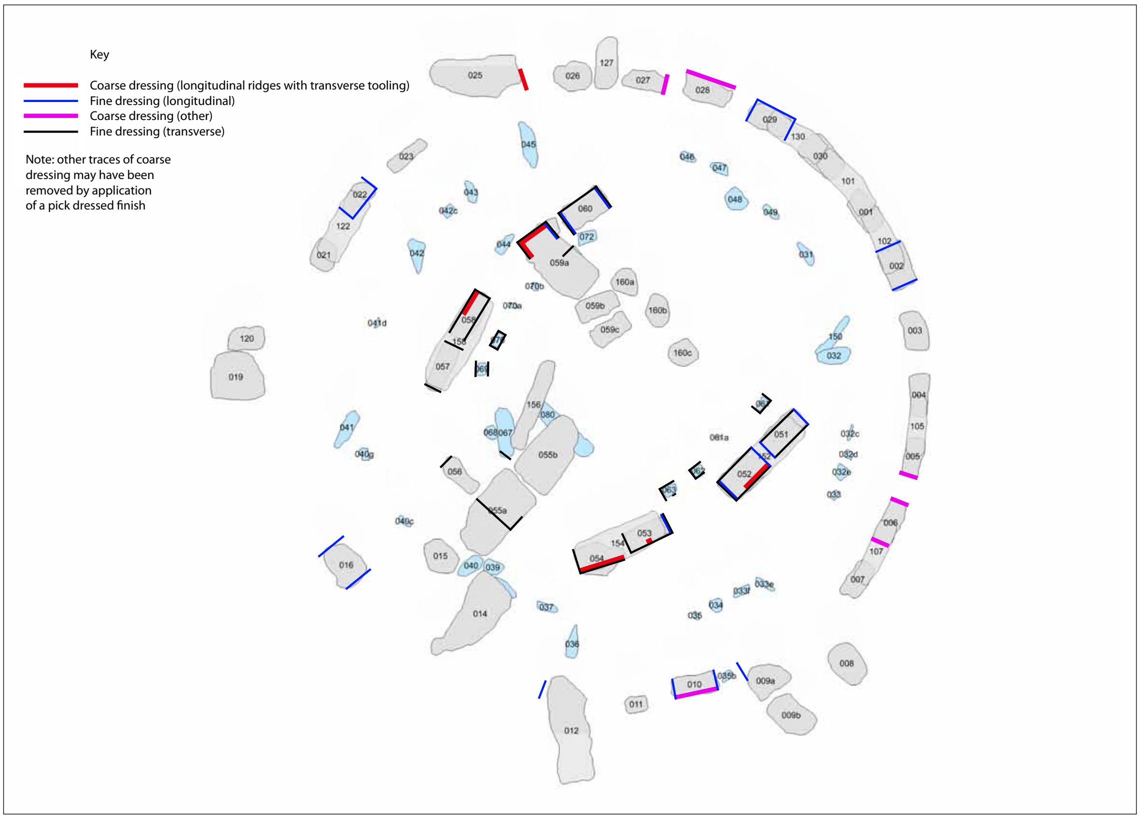

Figure 9b. Patterns of stone-working at Stonehenge: dressing visible beneath the surface finish

and well dressed, rectangular break between these stones reflects the significance of the NE-SW alignment of the monument; similar portals are present between Stones 30 and 1, and 15 and 16 of the Sarsen Circle.

The internal faces of Trilithons 1, 2, 4 and 5 are flat, with evidence for extensive dressing to produce a regular surface, except for Stone 60 which has a naturally very flat surface; all exhibit fine pick dressed surface finishes. In contrast, the sides of these stones are less uniformly dressed and the external stone faces are comparatively rough. All of these surfaces have been finished with pick dressing, but traces of coarse and fine dressing are clearly visible beneath this finish.

In contrast to the other trilithons, the internal faces of the Great Trilithon (Trilithon 3) are vertically convex, while the exterior faces are perfectly flat. The exterior faces have also been finished to a very high quality, indicating that the area behind this trilithon was an important location. Indeed, it is no doubt significant that midsummer sunrise can be observed from this point along the NE-SW axis of the monument.

The lintels present on all of the trilithons are exceedingly well worked and finished. These are the first feature one sees when walking along the Avenue from Stonehenge Bottom.

Two stone-working techniques employed on the Sarsen Horseshoe are of particular interest. Coarse dressing with longitudinal ridges and transverse tooling is a common feature on the exterior surfaces of Trilithons 1, 2, 4 and 5 (Stones 52, 53, 54, 58 and 59, and possibly the side of Stone 59), but this technique is not used elsewhere in the monument. The use of fine transverse tooling is even more intriguing as it found on all of the upright Sarsen Trilithons and on all of stones in the Bluestone Horseshoe that once formed part of Bluestone Trilithons. The fine transverse tooling is however only employed on one stone in the Sarsen Circle (a lintel rebate on Stone 122). The similarity between the dressing techniques present on the Bluestone and Sarsen Trilithons is clearly significant and it may imply that the stones were prepared at the same time, or that the dressing techniques visible on one set of trilithons informed the techniques used on the other. The absence of this technique on the Sarsen Circle is more difficult to explain, but it may be taken to suggest that the stones were prepared either at a different date, or by different people.

The above account has emphasised many common traits shared by the trilithons, but each trilithon has distinguishing idiosyncrasies. The stones employed as uprights appear to have been carefully matched and paired in each trilithon, but each trilithon is different (contra Whittle 1997). The stones in Trilithon 1 are very stocky, while those in Trilithon 4 are thin, and those in Trilithon 5 are very thick and bulky. The dressing of the uprights also subtly differs between trilithons, although the same stone-working techniques are employed. Trilithons 1 and 5 exhibit extensive use of longitudinally tooling (this is only present on one other face of the Sarsen Horseshoe, on Stone 53), while both uprights of Trilithon 4 exhibit comparatively fine transverse dressing on the sides of the stones.

Trilithons 2 and 3 share many affinities, such as the use of unusual purple-grey and orange sarsen and the application of very extensive surface dressing, but it can be argued that the stones have been mixed. Trilithon 2 employs two purple-grey sarsens (Stones 53 and

154) and one orange (Stone 54), while Trilithon 3 employs two orange sarsens (Stones 55 and 156) and one of purple grey colour (Stone 56). The mixing of the purple-grey and orange stones appears slightly incongruous and one wonders if the stones of a particular colour were at some point intended to be used together. It is, however, clear from the final pattern of dressing, *e.g.* the finely dressed exterior surface on Stone 55, that the pairing as it exists today was conceived before the stones were dressed (although it is notable how well Stones 53 and 154 are finished in relation to Stone 54).

Sarsen Circle

Flinders Petrie (1880) envisaged the Sarsen Circle as a structure of 30 uprights and 30 lintels. Today, only seventeen sarsen uprights are standing, including Stones 22 and 23 that have been re-erected; several other stones have been straightened and set in concrete. Stone 11, although standing, is broken and leans towards the south. Six of the proposed 30 lintels remain in place, including Lintel 122 that was re-erected, and two survive as fragments on the ground. The NE half of the Sarsen Circle is largely intact, while many stones in the SW half are missing, fallen and fragmentary. Prior to the current study, the most informative description of the tooling was provided by Richard Atkinson:

> *'A careful survey of the various degrees of tooling and polishing to which the stones have been subjected shows that the main concern of the builders was to produce a presentable finish on those surfaces which would be seen from the interior of the site. The best finish thus occurs on the inner faces of the uprights. Their sides have often been left in the second (shallow groove) stage of dressing, while their outer faces are frequently very rough, with large irregularities only perfunctorily reduced by deliberate coarse tooling.'*
> Atkinson 1979, 126.

The current study has significantly revised our understanding of this structure and a revised account is presented below.

Sarsen uprights

The stones employed as uprights in the Sarsen Circle vary in size and shape around the perimeter of the circle. With the exception of Stone 16, the largest stones are typically located to the east, while the smaller stones are located to the west; this reflects the fall natural contours of the site dipping east and the desire to create a level top to the circle (see Field and Pearson 2010, 9 Fig.5). The most regular and extensively dressed stones are however placed towards the NE, with the notable exception of Stone 16 which is located on the monuments NE-SW axis. The use of a small stones (e.g. Stone 11 and Stone 21) and irregular stones (e.g. Stone 14) is a distinct feature of the SW half of the monument.

The shape of the stone faces also varies around the perimeter of the monument. The NE side of the circle (Stones 22-30 and 1-9) is dominated by stones of trapezoidal form (18 interior/exterior faces: 77% of total), with only seven rectangular stones. In contrast, eight interior/exterior faces at the rear of the monument are rectangular (67% of the total), two are trapezoidal and two are amorphous. The use of trapezoidal stones provides a visual illusion of increased height. In previous accounts (*e.g.* Atkinson 1956) this optical illusion has been described as *entasis*, but this terminology has been incorrectly applied as few of the faces are convex and none of the stones swell at one third of their height. It should also be noted that the form of the gaps between the stones is of equal importance to the form of the stones. Most notably, the SW side of Stone 30 and NW side of Stone 1 have been carefully prepared to form a regular rectangle, comparable to the gap between Stone 55 and 56 of the Great Trilithon, while the adjacent stones exhibit a V-shaped gap comparable to the space between Trilithons 1, 2, 4 and 5. The SE side of Stone 16 is also exceptionally straight and well dressed, potentially indicating (in the absence of the NW face of Stone 15) that this too formed a regular rectangular sightline through the main NE-SW axis of the monument.

Examination of the faces and sides of the stones for evidence of dressing revealed that all surfaces were finely pick dressed, with the exception a few faces that were coarsely pick dressed, and the sides and external face of Stone 14 and the external faces of Stones 15 and 16 that were not worked. The absence of working on the exterior faces of Stones 14-16, and coarse finishes on the backs of Stones 10 and 11 is significant as these further demonstrate a significant contrast between the NE and SW sides of the monument, as well as indicating interior/exterior difference.

The working of the interior and exterior faces of Sarsen Circle was essentially limited to pick dressing over a natural sarsen surface. In effect, this dressing removed the grey or brown exterior crust of the stone and revealed the white interior of the stone. The only exceptions are the inner faces of Stones 10, 22 and 28 and the exterior faces of Stones 10, 11, 28 and 30, which exhibit limited areas that have been dressed slightly flatter than the original sarsen surface. In all cases any trace of the earlier mode of tooling was removed by the fine pick dressing, with the exception of the inner face of Stone 22 which exhibits faint traces of fine longitudinal tooling beneath the pick dressed finish.

The interior stone faces have been carefully selected and most are flat (17 of 21 faces; 77%). Only three interior faces are irregular and one is convex; notably if one stands at the centre of the monument the latter four faces are hidden from view behind the trilithons of the Sarsen Horseshoe. The external faces of the monument are less consistent, with nine recorded as flat (47%), nine as slight to very irregular (47%), one as convex and another as concave. This pattern of stone orientation indicates the importance of the view from the centre of the circle, but it cannot necessarily be to taken to suggest that the exterior view was less important. This is because the exterior of the monument is typically viewed at a reasonable distance, meaning that even the most irregular surface, such as the protrusion on the top of Stone 28, appears comparatively regular.

In contrast to the faces, the sides of the stones in the Sarsen Circle are typically extensively dressed. This dressing serves to create the regular rectangular and trapezoidal stone forms, visible from the interior and exterior of the monument. The surface finish of the sides of the stones was fine pick dressing and in many cases this has removed all traces of earlier tooling techniques. There is, however, limited evidence that the sides of these stones were initially shaped by splitting and/or flaking the sarsen. These actions would both produce significant quantities of sarsen waste. The sides of several stones exhibit slight traces of fine longitudinal tooling, but notably fine transverse tooling was not employed (a technique present on every stone in the Sarsen Horseshoe). It is difficult to explain this change in the approach to tooling, but it may indicate that the stones of the Sarsen Horseshoe and Sarsen Circle were dressed in chronologically separate events, or by different people.

All the tops of the uprights, where present, exhibit seats and tenons and, where the mode of tooling can be determined, they were manufactured by coarse pick dressing. Each seat and tenon exhibits some degree of individuality in its size, shape and positioning, indicating that they were probably prepared to the unique specifications of a lintel. It is worth noting that many of the tenons are comparatively slight and few are likely to have held a lintel securely in place. The tenons are typically circular, but one oval tenon was observed on Stone 16. Notably, the interior face of Stone 16 resembles the interior face of Stone 56, the only other stone with an oval tenon. It is, however, possible that this tenon is unfinished and that stones were erected with an oval ridge that would be dressed to a circle tenon when the precise position of the mortise on the lintel had been determined.

The tops of Stones 21, 22, 29 and 30 exhibit small breaks that appear to have occurred during construction of the monument. In the cases of Stones 21, 29 and 30, the break allows a mortise to be seen on the underside of the stone, and notably Lintel 122 on Stone 21 has a second set of mortises that were added to fit the stone presumably after the break occurred (Atkinson 1979). No lintel is in place above the break on Stone 22, and this reveals that the centrally placed, but small, tenon and seat must have been formed after the break occurred. The narrow width of this seat is, however, far from ideal for supporting a lintel. It is interesting to consider whether these breaks result from accidents, such as the dropping on a lintel on the top of a stone. Certainly, the break on Stone 30 could have occurred if Lintel 130 fell heavily on a protruding tenon.

Sarsen lintels

Six lintels of the Sarsen Circle survive in place, and two examples survive as fallen fragments on the ground. The lintels have been extensively shaped, with curved outer and inner faces matching the circumference of the monument. The final surface finish of the visible faces was fine pick dressing, where this could be determined, and this removed all traces of earlier dressing, with the exception of two small areas of fine longitudinal dressing on Lintel 102. Lintels 130, 101 and 102, on the NE half of the monument, are most regular lintels. Lintels 105 and 107 are of less regular proportions and the former is comparatively small, while Lintel 122 to the rear of the monument is very irregular and poorly shaped. This perhaps suggests that the quality of the lintels varied around the perimeter of the circle, with less regular examples located towards the back of the circle.

Stones 101, 102, 103 and 107 exhibit a vertical 'tongue' joint on their counter-clockwise ends and a 'groove' joint on their clockwise ends. Lintels 105 on 122, however, exhibit 'tongue' joints at both ends. This indicates that the missing lintel 106, along with other stones, must have had a groove at both ends. To some degree each lintel must have been tailor made, so such irregularities represent no particular issue, but it does convey an *ad hoc* approach to construction. On the few examples where dressing could be identified, coarse dressing was employed to shape the ends of the stones.

Nine rebates were identified on the stones. These provided minor adjustments to correct the level of the stone. Very coarse pick dressing was employed in four cases, coarse pick dressing in three examples, and fine transverse dressing in one example, whilst the mode of dressing could not be identified in one other case.

Detailed examination of the lintels revealed a number of features and irregularities not visible from the ground. Eight ribs are present on the stones, including vertical ribs close to each edge on the interior and exterior faces of Stone 130, and a similar rib on Stone 122. Further ribs were located on the tops of Stones 107 and 130, close to one side of the stone, and a smaller oval tenon-like projection was noted in a similar location on Lintel 105; the latter was associated with an oval mortise-type hollow. The purpose of these ribs is unclear, but they may have assisted in raising the stone (*e.g.* stopping bindings slipping off the edge of the stones). A large mortise-type feature is present on the top of Lintel 130, but unusually this is located in the centre of the stone; the purpose of this hollow is not known.

Outlying sarsen stones

Station Stones (Stones 91 - 94)

The two surviving Station Stones (Stones 91 and 93) are largely unworked, but limited areas of fine pick dressing are present on the N and S sides of Stone 93.

Slaughter Stone (Stone 95)

The Slaughter Stone has been extensively dressed, in a style comparable to the stones of the Sarsen Circle. The exterior NE face exhibits coarse longitudinal tooling and its NW side exhibits fine longitudinal tooling. Both of these surfaces and the SE side have been finished by the application of fine pick dressing.

Heelstone (Stone 96)

The Heelstone appears to be entirely unworked. The stone is largely free from modern graffiti, but an Ordnance Survey datum point was carved on the stone in the 19th century. A small chip was detached by a vandal with a hammer and screwdriver in 2008.

Bluestone Horseshoe

The Bluestone Horseshoe is generally thought to have consisted of 19 stones, although the sockets of three have not been located (Stones 61a, 61b and 68a; Cleal *et al.* 1995 214-24). Fourteen stones survive: six are standing and intact (61, 62, 63, 68, 69 and 70), two are fallen (67 and 71/72), two survive as ground-level stumps (64 and 65), three survive as below-ground stumps (66, 70a, 70b) and one stone is represented by a displaced fragment (61a). An additional array of four stone holes to the NE would have transformed the horseshoe into an oval, and one further stone hole located just inside the arc mirrors the position of the Altar Stone; none of these stones are present.

Laser-scan data were available for all six standing and both fallen stones. Traces of a fine transverse tooling, used to shape the stones, is present on all of the stones examined, with the exception of Stone 68. The latter, which exhibits a tongue-and-groove joint, is exceedingly finely pick dressed, and this finish has presumably removed all earlier traces of working. Fine pick dressing is present on most of the stone faces, overlying the fine transverse tooling where present, but the exterior faces of Stones 67, 69, 70 and 72 have been left at the earlier stage of dressing. It is also notable that the pick dressing on the exterior faces of Stones 61 and 62 is less intense than on the sides and front faces of the stones. It was not possible to examine patterns of dressing on the tops of the stones, as these data were not collected by the laser scanner, but it is significant to note that Stones 67, 69, 70 and 72 exhibit seats and traces of tenons that have been removed by pick dressing (Atkinson 1956).

The pattern of dressing on the stone faces is significant because it is the same as the trilithons of the Sarsen Horseshoe. This potentially has a bearing on how the Bluestone Trilithons were originally erected. Trilithons 1, 2, 4 and 5 are set with minimally dressed faces orientated towards the exterior of the monument; it is interesting to consider whether the dismantled bluestone trilithons may have been established in a similarly orientated arrangement.

Bluestone Circle

The Bluestone Circle is located between the Sarsen Circle and the Sarsen Horseshoe. Thirty stones survive, but originally there would have been many more; Paul Ashbee (1998) favoured a total of 56 stones, while Mike Pitts indicates that there may have been up to sixty or seventy (Pitts 2001, 137). Of the surviving stones, 8 are standing, 11 are fallen, 2 are displaced and 9 survive as buried stumps.

The overall structure of the circle is unclear but, in general, the stones increase in size towards the NE and the two most substantial stones (Stones 31 and 49) are placed with a wide gap straddling the main NE-SW axis of the monument. The stones in the Bluestone Circle include spotted dolerite, unspotted dolerite, rhyolite, rhyolitic and dacitic tuffs (Ixer and Bevins 2011a, Bevins *et al*., 2012), altered volcanic ash, sandstone with mica and calcareous ash (Atkinson 1956; Thorpe *et al*. 1991. However, the three latter stone types only survive as buried stumps, along with one stone of spotted dolerite and another of rhyolite.

The stones in this circle are largely unworked, with the exception of two spotted dolerite lintels (36 and 150), reused from an earlier structure that included bluestone trilithons. Stone 45 exhibits coarse pick dressing on its interior (now upper) face and very fine pecking on both sides. Stone 45 is therefore comparable to the uprights re-used in the Bluestone Horseshoe and one may speculate that the buried face is finely dressed; as has been observed on the stones of the Horseshoe. It may be significant that the roughest dressed face was orientated towards the centre of the monument when this stone was erected in the circle of largely undressed stones. The reused lintels, which were both originally erected in the Bluestone Horseshoe with their mortises facing the exterior of the circle, have fallen and are now largely buried. Richard Atkinson excavated both of these stones in 1954, lifting Stone 36 for the purpose of recording it, but both were re-buried in their original positions. Atkinson recorded transverse fine tooling on the outer end of lintel 150, but noted that the other surfaces had been worked smooth 'probably by fine overall pecking with light hammers' (Atkinson 1956, 137). He further noted that 'grinding seems to have been restricted to the production of the mortise holes on the two lintels, which are noticeably smoother even than those surfaces, such as the inner end of the lower surface of the lintel 36, which have always been protected from weathering' (1956, 137). Indeed, Atkinson considered Lintel 36 as 'among the finest achievements of the mason's craft in prehistoric Europe' (1956, 137).

Altar Stone

The Altar Stone was recorded as being finely dressed when it was excavated, but the small area currently visible is too worn from footfall to identify its mode of dressing (Atkinson 1956; 1960; 1979).

Decorating Stonehenge: prehistoric carvings

Background

In the late afternoon on 10th July 1953, Richard Atkinson was attempting to photograph the prominent 'IOH:LVD:DΣ FΣRRΣ' graffito on the NW face of Stone 53 as the sun cast it into shadow, when his eyes were attracted to the unmistakable form of a hilted dagger and an axe-head (Atkinson 1956, 31). Further examination by Atkinson and R.S. Newall revealed traces of 14 axe-heads '*and several vaguer markings, almost certainly artificial but much too eroded for even the most conjectural identification*' (*ibid.*). In the following weeks, further axe carvings were identified on Stone 3 and 4, and R.S. Newall discovered a 'quadrilateral' carving on Stone 57 (Atkinson 1956, 31). A second axe or dagger was identified on the SW side of Stone 53 by Mr Brian Hope-Taylor in August 1953 and, on New Year's Day 1954, Dr O.G.S. Crawford found a further dagger on the SW face of Stone 23, and a selection of other possible carvings (*ibid.*; Crawford 1954). Few carved motifs have been found since this initial flurry, with the notable exceptions of an axe on Stone 5 reported by Richard Atkinson in 1979 and the discovery of two new axe-heads on Stone 53 by ArchaeOptics/Wessex Archaeology in 2003 (Goskar *et al.* 2003). The latter were discovered by processing laser scan data and revealed the potential of this technique for identifying new motifs at Stonehenge.

All previously recorded carvings have been identified, plotted and re-interpreted. In addition, every stone surface was systematically examined for new prehistoric carvings.

Results

In total, 118 certain or possible prehistoric carvings were recorded. This number is dominated by carvings (certain or possible) of unhafted Early Bronze Age metal axe-heads (115); these carvings are located on Stones 3, 4, 5 and 53. Forty-four of these carvings were previously known, and 71 represent new discoveries. In addition, three previously known dagger carvings on Stones 23 and 53 were identified and examined. The daggers on the SW face of Stone 23 and the NW face of Stone 53 were substantiated, but the carving on the SW face of Stone 53 appears to be two axes rather than a dagger. A new possible dagger carving was located on the NW face of Stone 53.

This analysis has cast doubt on many of the poorly defined lines, hollows and irregularities previously identified as motifs (Stones 2, 9b, 23, 28 and 29). In addition, the ‘quadrilateral’ motif on Stone 57 has been re-interpreted as part of a wider area of stone dressing, and a comparable motif on fallen Lintel 120 has been re-interpreted as a rebate. Various ‘ribs’ have also been classed as areas of stone working rather than motifs (*e.g.* the rib on the SE face of Stone 53).

It is also frequently stated that cup-marks are present on the stones, although past accounts fail to specify locations. Numerous regular hollows (Figure 10) were located on the surfaces of the stones during this analysis, but all appear to represent natural irregularities (*e.g.* SW face of Stone 57, F.148) or casts of pebbles that have been lost (e.g. W face of Stone 30). Careful examination of all hollows and possible cup-marks, both in the laser-scan data and in the field confirmed that no working is present in the hollows.

Figure 10. Many natural hollows, such as these on the NW face of Stone 60 resemble cup marks but are natural irregularities in the sarsen surface. (Photograph Hugo Anderson-Whymark)

The catalogued examples of rock art are considered below, stone by stone.

Stone 2

A large flaccid phallus had previously been noted high up on the exterior NE face of this stone (F.242). This is an entirely natural stone form that has been pick dressed, along with the rest of the stone surface.

Stone 3

Three clear axe carvings were discovered down the exterior E face of Stone 3 by R.S. Newall in 1953 (Figure 11). Analysis confirmed the presence of these carvings; no new

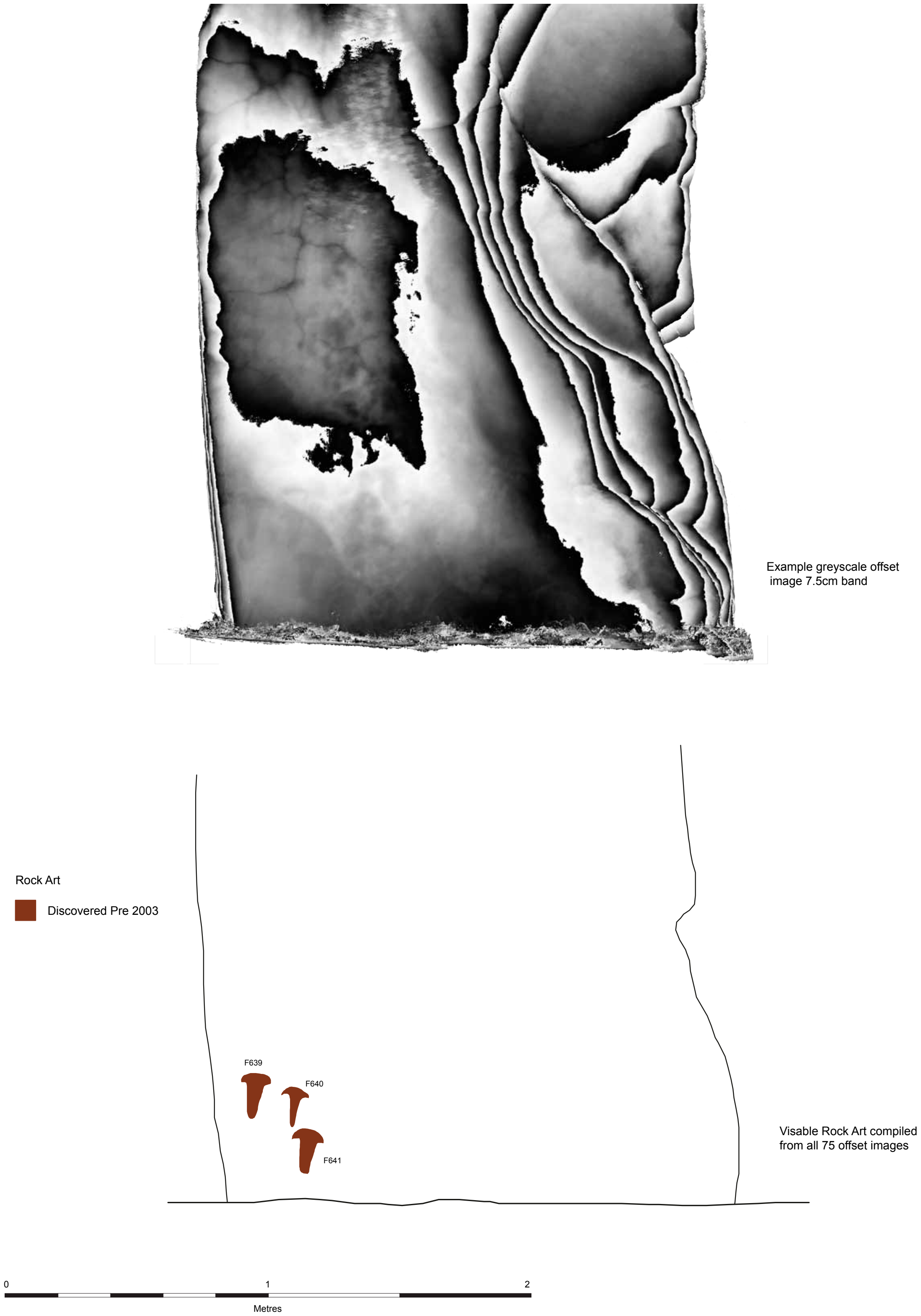

Figure 11. Axe-head carvings on the exterior east face of Stone 3

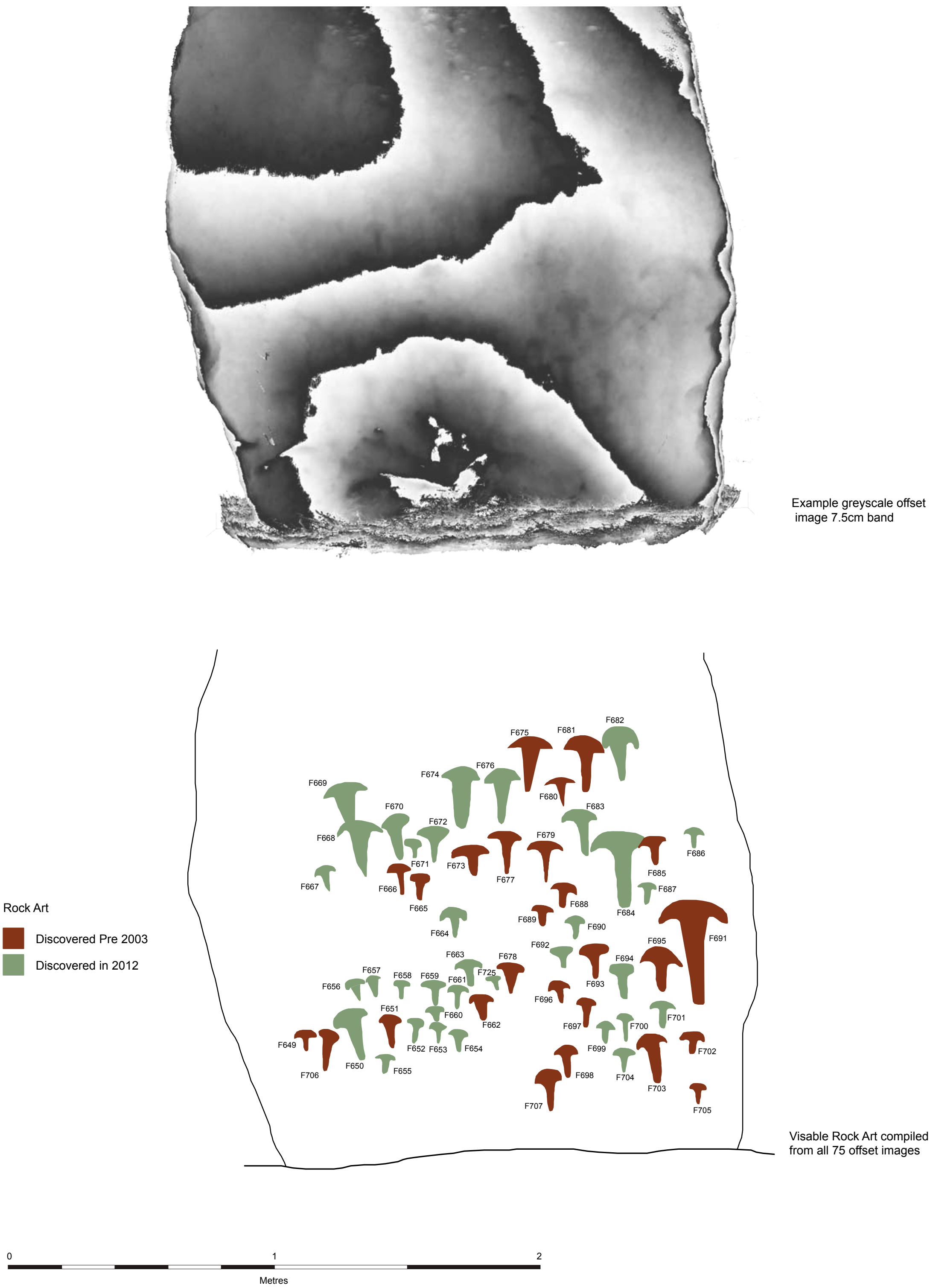

Figure 12. Axe-head carvings on exterior E face of Stone 4. Previously identified examples are highlighted

examples were identified. The three axe-heads are all unhafted with their blade edges upwards. All three axe-heads exhibit strong crescent-shaped blades characteristic of axes dating from *c.*1750-1500 cal BC, Needham's metal stage 4 (Needham 1996; Needham *et al.* 1998; Lawson 2007, 254).

Stone 4

Newall identified 26 carvings of axe-heads on the exterior E face of Stone 4, but Atkinson appears to have believed only about a dozen. Examination of the surface has revealed that 22 of Newall's 26 carvings are certainly genuine, one is a probable example and three are possible examples. An additional 33 axe-head carvings were identified (19 certain examples, seven probable examples and seven possible examples), bringing the total for this stone to 59 carvings (Figure 12). All of these carvings have their blade edges upwards and are discretely positioned on the stone surface, with the exception of carvings F.685 and F.687 that possibly overlie the faint carving F.684. The axes are distributed across the lower *c.*2 m of the stone face, particularly toward the N half of the face but, at the S side towards the base, two distinct rows of axe-heads are present. The axes are all broadly full-size, with the notable exceptions of axes F.684 and F.691 (both over-sized); the latter measures 36 cm long by 28 cm wide. None of the axes has exaggerated flanges, but most exhibit strong crescent-shaped blades characteristic of axes dating to *c.*1750-1500 cal BC. This is the largest panel of carved axes in Britain, and further analysis of the surface is likely to yield additional discoveries.

Stone 5

Richard Atkinson indicated that one axe-head was discovered on Stone 5, but the location of this carving was not recorded (1979, 209). Analysis of this stone revealed ten carvings of unhafted axe-heads with their blade edges uppermost. Nine of the axe-heads are present on the exterior E stone face and one is on the N side of the stone; all are located on the lower *c.* 2m of the faces, without overlap. Six of the carvings are considered to be certain examples (F.642, F.645-6 and F.701-2), two are probable (F.647 and F.719) and two are possible examples (F.643 and F.723, See Figure 13).

Stone 9b

Dr O.G.S Crawford identified a snake-like carving (F.271) and various irregular hollows on the surface of Stone 9b, but he could not decide if these were of natural origin (Crawford 1954). Examination of these markings indicates that they are all natural features enhanced by surface weathering.

Stone 12

A wide, flat based, circular depression (F.309) is present low down on the interior N face of this stone. This mark, along with the whole stone face, exhibits fine pick dressing. It is possible that this mark represents a natural irregularity on the sarsen surface that has been dressed along with the rest of the face rather than a deliberate carving. The mark is, however, regular and broadly central to the face, so the possibility that it was deliberately carved cannot be entirely discounted.

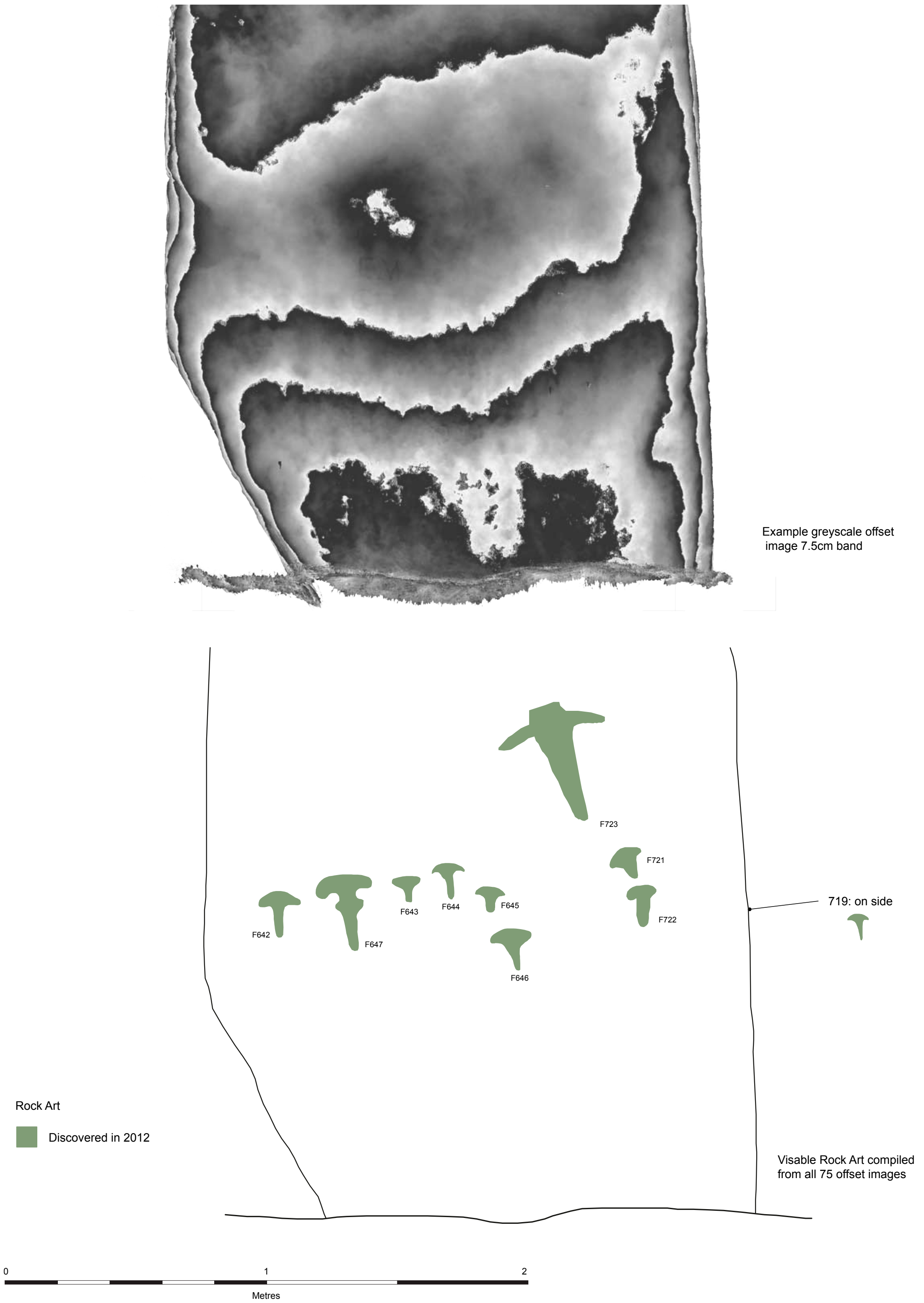

Figure 13. Axe-head carvings on exterior E face of Stone 5

Stone 14

A natural foot-shaped depression is present toward the base of the exterior face of this stone. This mark is associated with the myth of the devil casting the Heelstone at a friar, and it supposedly represents the mark left by the devil's foot (F.710).

Stone 23

On New Year's Day 1954, Dr O.G.S. Crawford identified a carving of a small dagger on the SW side of Stone 23 (F.364, see Figure 14). This carving is commonly illustrated as appearing on the SE interior face of the stone as Crawford simply described the carving as being on the S face (e.g. Cleal *et al.* 1995, 30, Fig.17); this is incorrect. A superb photograph of the carving appears in Crawford's 1954 article on the carvings that he discovered and this shows a short blade with a clear handle and pommel. This carving exhibits a deeply incised outline, but the central area has not been lowered by pecking. This technique of manufacture was not employed on other prehistoric carvings, but there is no reason to suspect that this carving is not prehistoric.

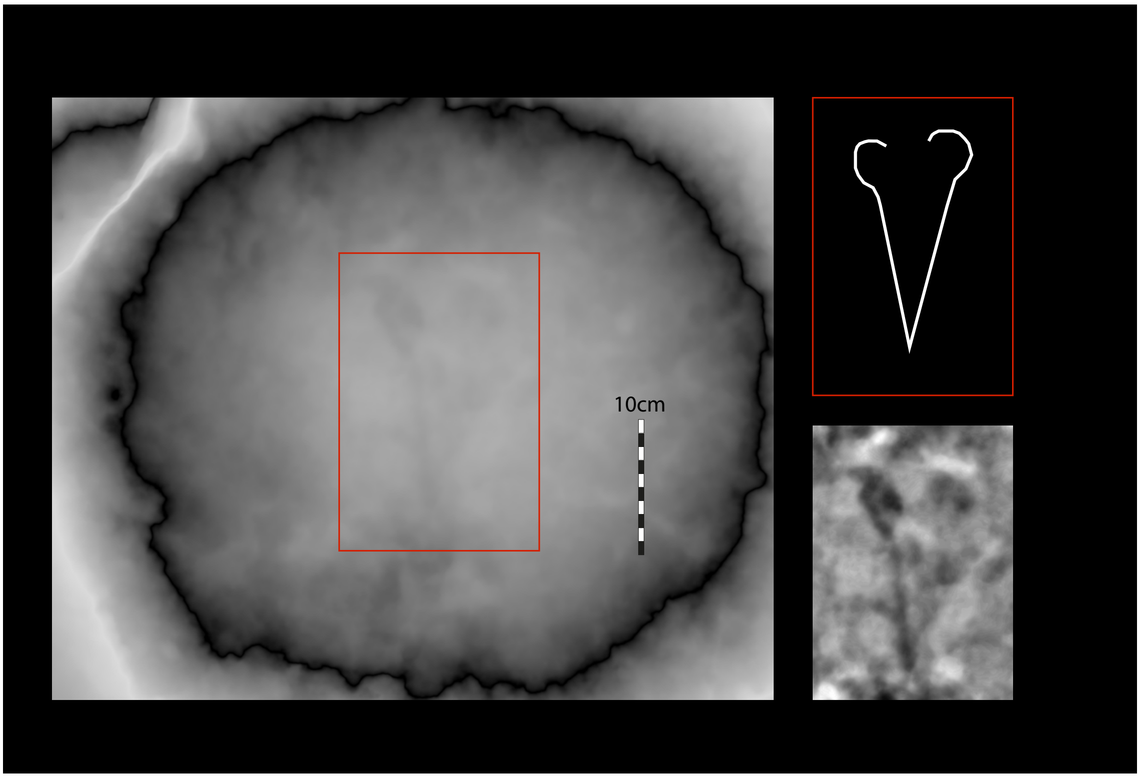

Figure 14. Dagger carving on the SW side of Stone 23

Stone 28

The exterior N surface of this stone is commonly said to resemble a face (e.g. Chippindale 2004). The 'face' is created by the natural fracture pattern of a sarsen and none of the features have been deliberately enhanced. Indeed, the whole surface has been coarsely pick dressed partially removing features, so there is no reason to suspect that the builders of Stonehenge deliberately selected this stone because of the 'face'.

Stone 29

Dr O.G.S. Crawford discovered a 'torso' carving 16 inches (406.4mm) in height on the south side of Stone 29 on 1st January 1954 (Crawford 1954, Plate VIIb; Atkinson 1979, 44; Cleal *et al.* 1995, 31). We suspect that this supposed motif is on the SW side of the stone, but no convincing carving could be identified.

Stone 53

The interior NW face of Stone 53 exhibits a deeply carved dagger and axe, in the centre of the face, *c.*1m above ground level. The dagger has a long slender blade and a prominent hilt with concave sides to the grip, and a flat or slightly convex pommel. Its overall shape, however, finds few parallels with British or northern European bronze daggers. The axe is unhafted and orientated with its blade upwards. The position and depth of these carvings indicate that they are possibly the primary motifs on the panel. It should also be noted that the lower two metres of this face has been ground to a smooth finish.

Atkinson and Newall identified 13 additional, shallow, axe-head carvings on this surface. These carvings have all been identified and 12 are certainly genuine, one is considered a possible carving. In addition, a further 28 axes have been identified, including a further 12 certain examples, six probable examples, seven possible examples and 3 doubtful examples. This makes a total of 42 axe-head carvings on this stone face (Figure 15). Four examples exhibit exaggerated flanges (F.596, F.601, F.609 and F.618) and several examples exhibit very distinct crescent-shaped blades characteristic of axes dating to *c.*1750-1500 cal BC. The axes are all broadly full-size, although a few examples are possibly slightly enlarged (F.595, F.596, F.601 and F.613), and all examples have the blade edge upwards. It is also notable that the carvings are carefully positioned in relation to each other and very few even touch, let alone overlap. This indicates that the earliest carving was still clearly visible when the last carving was produced.

In addition to the new axes, a possible new dagger was recorded (F.600, see Figure 16). This carving is very shallow, but it bears remarkable similarities to Atkinson's dagger carving (F.611). The blade edge is very narrow, unlike the axe butts, and there appears to be a clear hilt with concave sides to the grip and a wide pommel. However, in terms of scale, this carving is much smaller than Atkinson's example.

In August 1953, Mr Brian Hope-Taylor identified a small 'hilted dagger' carving on the SW side of Stone 53 (Figure 17). Atkinson commented that 'certain peculiarities of its form suggest that it was originally carved as an axe-head, and it was later converted to a dagger by adding a hilt and a pommel and by lengthening the tapering butt of the axe to form a pointed blade' (1956, 32). Examination of the laser-scan data for this side of the stone indicates that this carving is two axes positioned above one another, rather than a dagger (F.638).

On the exterior SE face of Stone 53, a rib (F.93) and two irregular nicks are occasionally interpreted as a human face. This rib has been interpreted as the remnants of coarse tooling of a type common on the rear faces of the stones that form the Sarsen Horseshoe.

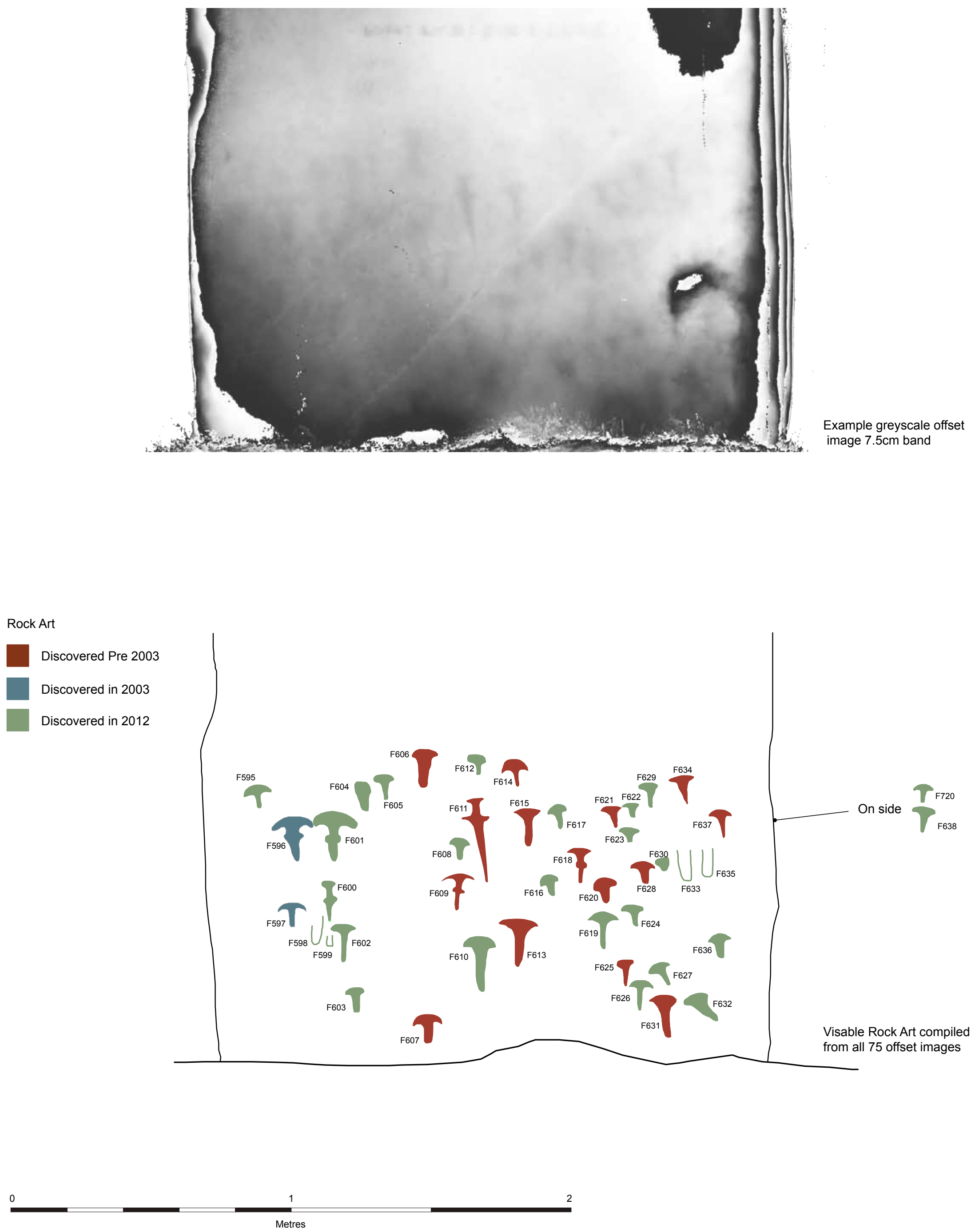

Figure 15. Dagger and axe-head carvings on interior NW face of Stone 53. Previously identified examples are highlighted

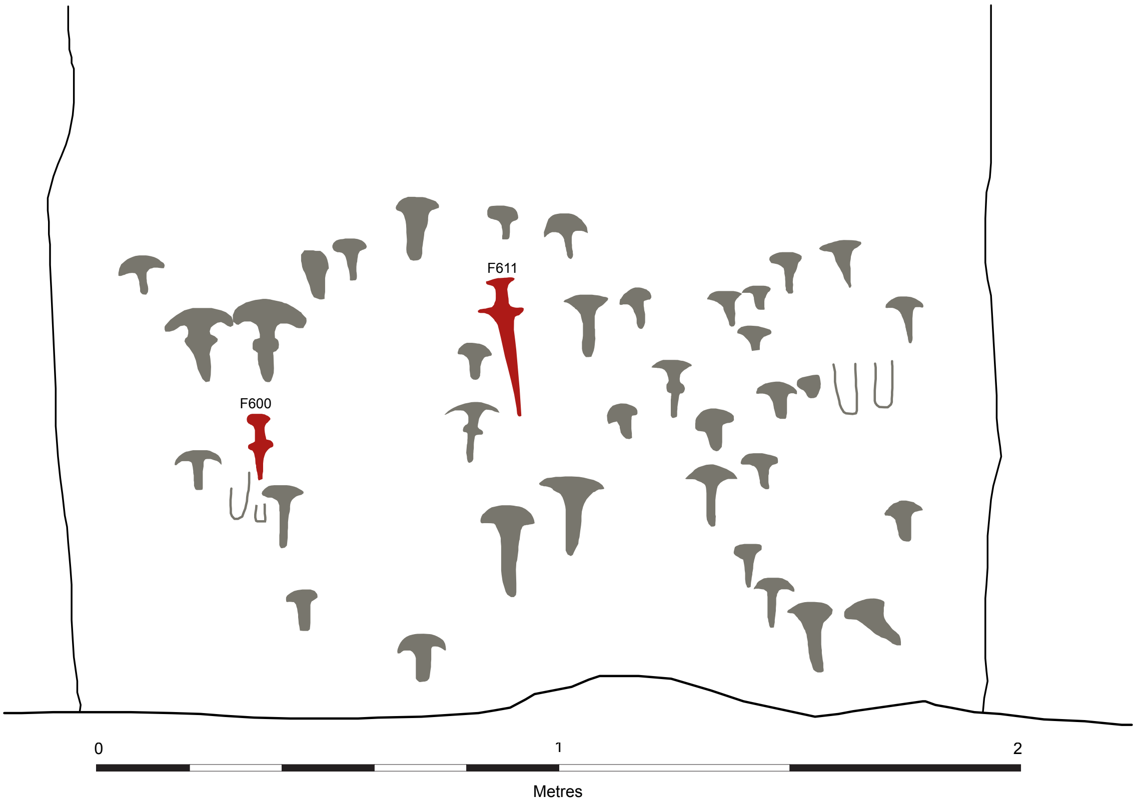

Figure 16. Close up of Atkinson's dagger (F.611) and the newly discovered possible dagger (F.600)

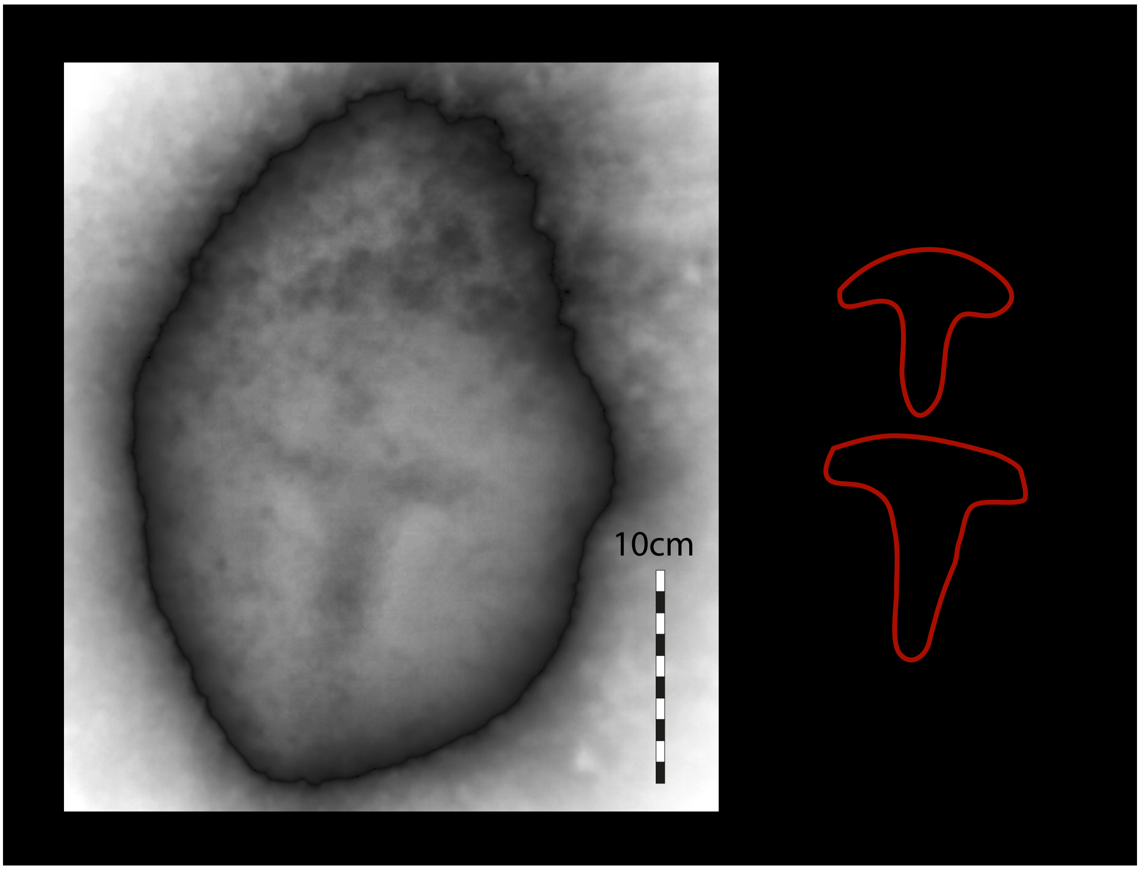

Figure 17. Dagger or axe-head carving on the SW side of Stone 53

Stone 57

A quadrilateral symbol was recorded on this stone by R.S. Newall in July 1953 (Figure 18). This symbol has been the subject of much debate, as it was initially reported as a Breton-style 'shield-escutcheon' or box-goddess symbol (Atkinson 1956, 32). This interpretation has long been questioned; not only is the carving unclear but radiocarbon dating has placed the Breton carvings millennia earlier than Stonehenge (Lawson and Walker 1995, 30-34; Lawson 2007). The laser-scan model reveals this 'quadrilateral' to be part of a much larger complex of lines that appear to relate to the pick dressing of the surface. Notably, rectangular panels, possibly representing the working area of individual stone masons, are present on a number of stones (*e.g.* Stones 12, 54 and 60).

Figure 18. The 'quadrilateral' carving, reinterpreted as an area of stone-dressing, on the SE face of Stone 57

Stone 120

A quadrilateral symbol, comparable to that observed on Stone 57, was noted on this stone by Mr Brian Hope-Taylor. This has been re-interpreted as the rebate on a lintel.

Discussion

The programme of analysis has confirmed the existence of all previously identified axe and dagger carvings, and it has revealed many more carvings on the known panels. It should be noted that many of the axe-head carvings are clearly visible on the 1mm laser scan model used to examine all of the stone surfaces, but no possible carvings were located elsewhere. The faces of various other stones were also examined using Plane Shading and Luminance Lensing, but without success. The limited distribution of the axe-heads on selected faces of Stones 3, 4, 5 and 53 is therefore considered genuine. It is also clear that the axes and dagger are carved low down on the stones, at a level that can be reached when standing or sitting on the ground surface. This is consistent with these carvings having been made after the stones were erected.

It has previously been observed that all of the axe-heads have been carved unhafted with their blade edges upwards, while the daggers have their blade pointing to the ground, and that each carving is separate, occupying a discrete area of the stone (Atkinson 1956; Lawson and Walker 1995; Lawson 2007). The newly discovered axes confirm these observations, with the possible exception of a couple of axes that overlie a faint carving on Stone 4. Indeed, the two lines of axes on Stone 4 indicate that some carvings were carefully positioned alongside one another. This pattern indicates that all but the faintest of axe-head carving was visible when the last motif was pecked into each stone face. This may suggest that the motifs were all cut within a comparatively short period of time, around *c.*1750-1500 cal BC.

Parallels for carvings of Early Bronze Age axes and daggers are few and far between, and only five certain parallels can be cited. The closest example is the 'Badbury Barrow' located some 6 km NW of Wimbourne Minster, Dorset, which, during excavations in the early 19th century, yielded a slab of sandstone with two carvings of hilted daggers and two carvings of unhafted axe-heads, along with five cup marks (Piggott 1939; Grinsell 1959; Lawson 2007, 253). A possible dagger or halberd carving was also recently identified on a stone at Calderstones, Liverpool, which once formed part of a monument (Nash and Stanford 2009; 2010) This motif was carved in outline only, and in this respect it is comparable with the dagger carved on Stone 23. The three remaining examples are found in burial cairns forming part of a monument complex in the Kilmartin Valley, Argyle and Bute. The inner face of the capstone for the central cist of the Nether Largie North Cairn exhibits at least ten axe-head carvings, which overlie numerous cup-marks, and two further axe-head carvings are visible on the side of the cist. Further along the valley at the Ri Curin Cairn, the side of a cist exhibits seven pecked axes, while the side of another cist at Kilbride exhibits three probable axes (RCHMS 2008). The association of axe and dagger carvings with funerary monuments is of particular significance to our interpretation of the carvings at Stonehenge which, at the time these carvings were made, was the central focus for the largest grouping of barrows in Britain.

The discovery of 71 new axe-head carvings increases the total number at Stonehenge to 115 (an increase of 161%) and it increases the total number of carvings known in Britain to 139 (an increase of 104%). Only six carvings of daggers are known in Britain, of which three are at Stonehenge.

Breaking Stonehenge: evidence for stone-breaking and the removal of stones

Although a large number of stones survive at Stonehenge, the monument is nowhere near complete. This has led many authors, including John Wood (1747), William Flinders Petrie (1880), Paul Ashbee (1998) and Christopher Tilley *et al.* (2007) to question whether the monument was ever finished. The non-completion theory is in part based on the use of what have been perceived as small and inadequate stones in the monument (*e.g.* Stones 11 and 22), but it also relies on limited evidence for the removal of stones and slighting of the monument (Ashbee 1998). It is certainly true that there is no documentary evidence for the removal of stones or deliberate slighting, unlike Avebury, but it is questionable whether we would expect such documents for a site located well away from medieval settlement. The current project has, however, revealed physical evidence for stone-breaking and the removal of stones. This evidence is presented below in relation to the main structural elements, and its implications for the non-completion theory are explored in the discussion.

Sarsen Circle

The Sarsen Circle envisaged by Petrie (1880) was composed of 30 uprights and 30 lintels. Sixteen uprights survive complete, the majority of which are located on the NE half of the monument, and one upright is broken (Stone 11). Two uprights lie complete on the ground (Stones 12 and 14) and a further six uprights are represented by broken fragments (8, 9, 15, 19, 25 and 26). Five uprights are not present at Stonehenge, although they were speculatively numbered by Petrie (Stones 13, 17, 18, 20 and 24). Of the 30 lintels, six survive in place (Lintels 101, 102, 105, 107, 122 and 130) and two are represented by fragments on the ground (Lintels 120 and 127); 22 are not present on the site.

The sarsen upright, Stone 11, requires special consideration as there has been much debate over its size and whether it is broken. Examination of the laser scan model revealed that the stone is dressed, to some degree, on all sides, but the top of the stone is broken. Careful examination of the edges of this break indicates that it truncates the dressed surfaces. As Stone 11 is the only upright that is broken, it is worth considering if this stone fell and broke at some point in its history, but was subsequently re-erected. It has been argued that such a sequence is too complex (Field and Pearson 2010), but it is not entirely implausible since Stone 40 at Avebury appears to have fallen and been re-erected in the Bronze Age (Ros Cleal *pers. comm.*). It should also be noted that, if Stone 11 was originally of full height and remained the same width to its top, the area for lintel seats and tenons would be limited but no less deficient than similar areas on many other stones (*e.g.* Stones 2, 6, 21, 22 and 29).

At this juncture it is significant to note that only one of the 23 standing stones is broken (4.4%), while eight of ten fallen stones are broken (80%). This pattern may indicate that sarsen stones are prone to breakage when they fall; however, of the six stones for which we have historical records of their fall (Stones 57, 58, 158, 22, 122 and 23) only one broke when it fell to the ground (Lintel 122). This may indicate that not all of the stones of the Sarsen Circle that lie on the ground were broken by the force of their fall. Moreover, none of the broken stones on the ground are complete. The state of the fallen stones has previously been used to suggest that these stones were never erected, but the carefully dressed seats and lintels of Stones 9, 15 and 19 lie precisely where one would expect a c.4.25 m high stone to fall if it toppled on its axis at ground level. Indeed the tops of Stones 14 and 15 are almost perfectly aligned on the ground. There can be no doubt that these fallen fragmentary stones once stood, firmly indicating that significant portions of them have been removed from the site, potentially after the stones were deliberately broken. Indeed, it is estimated that the missing fragments of Stones 8, 9, 11, 15, 19, 120, 26 and 127 would collectively weigh many tons. This demonstrates that a significant quantity of stone was removed from Stonehenge at some point in the past, probably in the historical period (even though documentary records for this removal are absent).

It is therefore pertinent to ask if there is any evidence that the missing uprights (Stones 13, 17, 18, 20 and 24) were ever present at Stonehenge? In summary, there is certainly good circumstantial evidence that all of these stones may have been present. The presence of fallen Lintel 120 can be taken to suggest that Stone 20 was once present and erect. Hawley excavated a stone hole for the missing Stone 13 and, within its backfill, there was evidence that a stone had been broken up. He noted that the stone had

> 'entirely disappeared, and from the irregular state of the top of the pit it may have been intentionally taken out and broken up, as large angular pieces of sarsen were found around the place' (Hawley 1926, 10 cited in Cleal et al. 1995, 194).

It should also be noted that a 1574 illustration of Stonehenge by Lucas de Heere appears to show Stones 13 and 14 standing with the now missing Lintel 114 in place (Stone 1924, 148). There may be some degree of artistic licence, but it could be significant that Stone 14 was depicted as leaning in various 18th century illustrations; it appears to have reached its current recumbent position only by the early 19th century.

The surviving tenons on the uprights may provide another means of considering whether lintels and missing uprights were once present. In order to achieve an accurate alignment, one of these elements has to be manufactured first, so the location of the other element can be accurately determined. Richard Atkinson believed that it was the mortises that were prepared first. He based this interpretation on the examination of Lintel 122 that exhibits two pairs of mortises:

> 'The deeper and wider pair were set symmetrically, in equal distances from the ends of the lintel. The shallower pair, on the other hand, though separated by the same distance from each other, were offset by about twelve inches towards Stone 21, so at this end the mortise was very close to the end of the lintel.' (Atkinson 1979, 208)

The shallower pair of mortises appears to have been cut following the detachment of a piece of upright Stone 21 during erection, which left one of the pre-prepared large mortises hanging over the void left by the detached fragment of Stone 21. This led Atkinson to state:

> 'From these observations we may conclude that the mortises in this lintel (and very probably in all lintels) were pre-fabricated while the lintel was still on the ground, and that the corresponding tenons on adjacent uprights were then worked to the correct distance apart.' (Atkinson 1979, 208)

If this is correct then the presence of a tenon would indicate that a lintel once existed on the upright. Notably, tenons are present on the tops of Stones 16, 19 and 23, which are adjacent to the three missing uprights and, by implication following Atkinson's argument, these stones must have been present to support the lintels. This argument also has significant implications for the missing lintels as the only locations where tenons are not present are the damaged/missing tops of Stones 5 (S side only), 8, 9 (NE side only, 11, 15 (NW side only), 21 (SE side only), 25 and 26. The surviving tenons may therefore indicate that 18 of the 22 missing lintels were once present.

Some caution is, however, expressed about using the presence of tenons to suggest that lintels were once present. Atkinson's argument is convincing for Lintel 122, but not all lintels were necessarily constructed in the same manner. Indeed, the presence of two tongue joints on some lintels and a tongue-and-groove on others indicates that construction was not necessarily consistent or systematically planned.

It should also be noted that the tenon on the NW side of Stone 16 is anomalous, as it is an elongated oval rather than a circular domed form. It has been argued above that this may represent a deliberate attempt to replicate the oval tenon on Stone 56, but equally it may represent the site of an unformed tenon, *i.e.* the ridge would be reduced to a circular tenon once the precise location of the mortise had been determined. If this is the case then this ridge may indicate that a lintel was not positioned on one side of this stone.

Sarsen Trilithons

The stones of the Sarsen Trilithons are essentially all present at Stonehenge, although small fragments of fallen Stones 55, 59 and 160 are missing from the site, and some stones have been extensively damaged by visitors causing flaking of their surfaces.

Outlying sarsens (Heelstone, Stations Stones and Slaughter Stone)

Two of the four Station Stones are missing, and two empty stone holes have been located adjacent to the Slaughter Stone (Hawley's stone holes D and E). A further empty stone hole (97) is adjacent to the Heelstone. The total number of outlying sarsens is however uncertain as large areas of the site remain unexcavated and these empty stone holes may reflect the position of stones that have subsequently been moved, rather than missing stones (e.g. Socket 97 may once have held the Heelstone).

The surviving stones are all intact, but direct evidence for medieval/post-medieval stone breaking is provided by a row of six wedge holes across the base of the fallen Slaughter Stone (Stone 95), that were intended to detach a fragment using the plug-and-wedge technique. It is also notable that an attempt was made, at an unknown date prior to the 19th century, to bury the Slaughter Stone in a large hole. This act can certainly be construed as a deliberate attempt to slight the monument, although for what purpose is unclear.

Bluestone Circle

The Bluestone Circle contains 30 stones, but originally it may have consisted of up to 70 stones. Nine stones survive as buried stumps (and other stumps may exist in unexcavated parts of the monument), but empty stone holes were identified in Atkinson's excavations, potentially indicating the removal of some stones from the site. Only seven of the 21 complete stones present in this circle are upright (Stones 31, 33, 34, 37, 46, 47 and 49), and most of these are the larger stones located on the NE side of the circle.

It should also be noted that a single rhyolite chip appeared to have been deliberately placed on the base of each of the excavated Z and Y holes (Atkinson 1956, 21). This may indicate that a stone of rhyolite was being worked or broken when these features were excavated. However, none of the above ground surfaces of rhyolite/dacitic stones appear to have been flaked.

Recently, considerable attention has been paid to the loose, non-doleritic bluestone material within the Stonehenge Landscape the so-called 'debitage'. Whilst very little of this material can be matched to the present standing stones much may belong to the stumps –indeed, rhyolite stump 32e has been proposed as the possible origin for much of the banded rhyolite debitage scattered throughout the Stonehenge Landscape (Ixer and Bevins, 2011a 2011b; Bevins *et al.* 2011; 2012).

Bluestone Horseshoe

In comparison with the Bluestone Circle, the Bluestone Horseshoe appears to be largely complete with 14 of 19 stones surviving: six are complete and upright (Stones 61, 62, 63, 68, 69 and 70), one is complete and fallen (Stone 67), one is fallen and broken into two fragments but complete (Stone 71/72), two survive as ground-level stumps (Stones 64 and 65), three survive as buried stumps (Stones 66, 70a and 70b), and one is represented by a displaced fragment (61a). The presence of six fragmentary stones indicates that at least a third of the stones in this setting have had significant portions removed from the site. Moreover, if the five stones that are entirely missing are taken into account, one may consider that approximately half of the stone employed in this structure is no longer present at Stonehenge.

An additional five stones from a NE extension of the Bluestone Horseshoe, which created an oval stone setting, are all missing (stone holes WA2717, WA2726, WA2749, WA2760, WA2730; Cleal *et al.* 1995, 215, Fig. 116). The complete absence of these stones may indicate that this end of the structure was systematically dismantled at some point in the monument's history, with the stones perhaps used elsewhere in the structure.

Conservation assessment

Stone 60 exhibits a substantial area of concrete infill at its base on the NW side. The stone was straightened and the infill added in 1959. This concrete fills a large hollow that Richard Atkinson and Herbert Stone considered to be the product of weathering, however examination of NW face of Stone 60 reveals that it is dressed over an irregular natural sarsen surface, and this dressing extends to the edge of the concrete plug. This irregular hollow was therefore present when the stone was erected. Close inspection of the fabric of the concrete, and the interface with the concrete and stone, revealed no damage or breakdown of the material. Near the base, where the concrete was quite thin, a small piece had broken off, but this looks to be physical damage rather than erosion or breakdown of the concrete. The revealed stone surface was substantially cleaner than the rest of the stone surface which may indicate that a thin layer of the stone surface was removed when the concrete broke away.

Stone 51 has *c*.0.15m diameter hole, probably of natural origin, at waist height on the SE face. A quantity of concrete had been poured into this hole, purpose unknown. The concrete has large stone/pebble inclusions and is stable.

Stone 58 exhibits a longitudinal joint that was pinned in 1958 to ensure the stone would not fail when it was re-erected by Richard Atkinson. Details of this restoration are held in English Heritage's archive. The pins set within the stone and concealed from view by replacing the plug of sarsen. Three subtle circular marks approximately 2 inches in diameter are visible to the naked eye on the NW face, but these are not clear in the laser scan data as the plugs are flush with the stone surface.

Lintel 122 fell on 31st January 1900 and broke into two fragments. This stone was repaired using metal pins and adhesive when it was re-erected in 1958. Details of this restoration are held in English Heritage's archive. The adhesive is visible on the lower surface and some staining is present around the join. This should be monitored to ensure the integrity of the repair.

Several other stones, which had been re-erected, also have concrete supports but these are below ground and obscured by vegetation, and so it was not possible to inspect these for damage at the present time.

A few of the stones show evidence of bird droppings, but this is not extensive and does not appear to be causing damage to the stones. The height at which this is occurring precluded a detailed inspection on site.

The impact of visitors on Stonehenge

Stonehenge has attracted and intrigued visitors from the earliest times. Some of these early visitors were drawn by the desire break and remove stones, perhaps for profit or religious zeal, but others came purely out of interest as tourists of their age. Lucas De Heere, an exile from Ghent, visited and illustrated Stonehenge in 1574 as part of a tour of Britain and Ireland that was ultimately published in his guide book, '*Corte Beschryvinge van England, Scotland, ende Irland*', written in his native tongue (Chippindale 2004). These early visitors were perhaps only occasional, but academic and popular interest vastly increased in the 17th and 18th centuries through the enquiries of Inigo Jones (1655), John Aubrey (1666), William Stukeley (1740) and John Wood (1747), among others. By the 19th century, Stonehenge was a popular tourist attraction and visitor numbers continued to rise through the 20th century; today almost a million people visit Stonehenge each year. Visitors to Stonehenge have left their traces on the stones in a variety of ways, from incidental damage from footfall to the carving of names and taking of chips of stone as mementos. The key types of visitor damage are described below.

Graffiti

Forty-four prominent examples of graffiti were recorded. These are, however, the tip of the iceberg and many hundreds of scratched and fine graffiti are also present on the stones. These slight graffiti are too fine to appear on the 1mm laser scan model, and many cannot even be seen on the 0.5mm model. In general, a higher resolution scan would be required to detect such fine traces, but it should also be noted that a specific problem of this data set derives from the use of oblique scans to capture many of the stone surfaces. Oblique scans simply cannot penetrate the full depth of narrow incisions and, as a result, even some graffiti that is clear to the naked eye is barely visible in the laser-scan models (*e.g.* carvings on the exterior SE side of Stone 52 and the NW side of Stone 56).

The graffiti recorded comprise many initials, first initials and surnames, surnames and occasionally full names. In eight cases, a name or initials is accompanied by a date and, in two cases, the visitors' home town is recorded. An occupation, or perhaps a group affiliation, is suggested by the prominent inscription '1802 (J.DAY W.LAW) MASONS CAMBERWELL' on the exterior of Stone 56, depending on whether it refers to stonemasons or Freemasons.

The earliest inscription, dated to the 17th century on stylistic grounds, is the deeply carved and heavily weathered 'IOH:LVD:DΣ FΣRRΣ' on the interior face of Stone 53 (Atkinson 1956, 31). This carving, which employs Greek sigmas instead of the letter 'E', is interpreted as Johannes Ludvicus [John Louis] De Ferre (*ibid.*). No individual of this name has been traced to the 17th century, but a John Louis De Ferre was christened on 8th May 1802 at St Peter Le Poer, London, and he died at Pancras, London, in 1884, aged 83. The heavy weathering of the carving indicates that it may have been of some antiquity when this individual was born, but the occurrence of the name is of interest. Christopher Chippindale (2004) observes that the name John Louis De Ferre 'is tantalisingly close to, but inescapably different from Lucas De Heere', the exile from Ghent who illustrated Stonehenge in 1574. The mystery surrounding this carving remains.

Another potentially early carving, although undated, is that of 'I WREN' on the SW side of Stone 52, attributed to the acclaimed architect Sir Christopher Wren (20th October 1632 – 25th February 1723).

The eight dated carvings include two from the 18th century, 'D.C. 1721' on the exterior, now upper, face of Stone 55b and 'H.G. 1735' on the back of Stone 59b, and six from the 19th century. The latter include 'W. SKEAT' and 'TOM SENIOR', who prominently carved their names in 1814 and 1817 on the exterior faces of Stones 28 and 23, respectively. The most recent dated carving is that of 'H. BRIDGER 1866 CHI. SUX' on the exterior face of Stone 4 (Figure 19). The dated graffiti span a period of increasing interest and visitor numbers to Stonehenge, and the latest date – 1866 – coincides with a period of increasing concern about damage caused to ancient monuments, leading ultimately to the introduction of the Ancient Monuments Act of 1882.

Graffiti was widely distributed across the monument, but the Stones 53, 55 and 156 have been most intensively inscribed (29 of 44 records). Notably, the raw material for these stones was the purple-grey (Stone 53) and orange sarsen (Stones 55 and 156). The

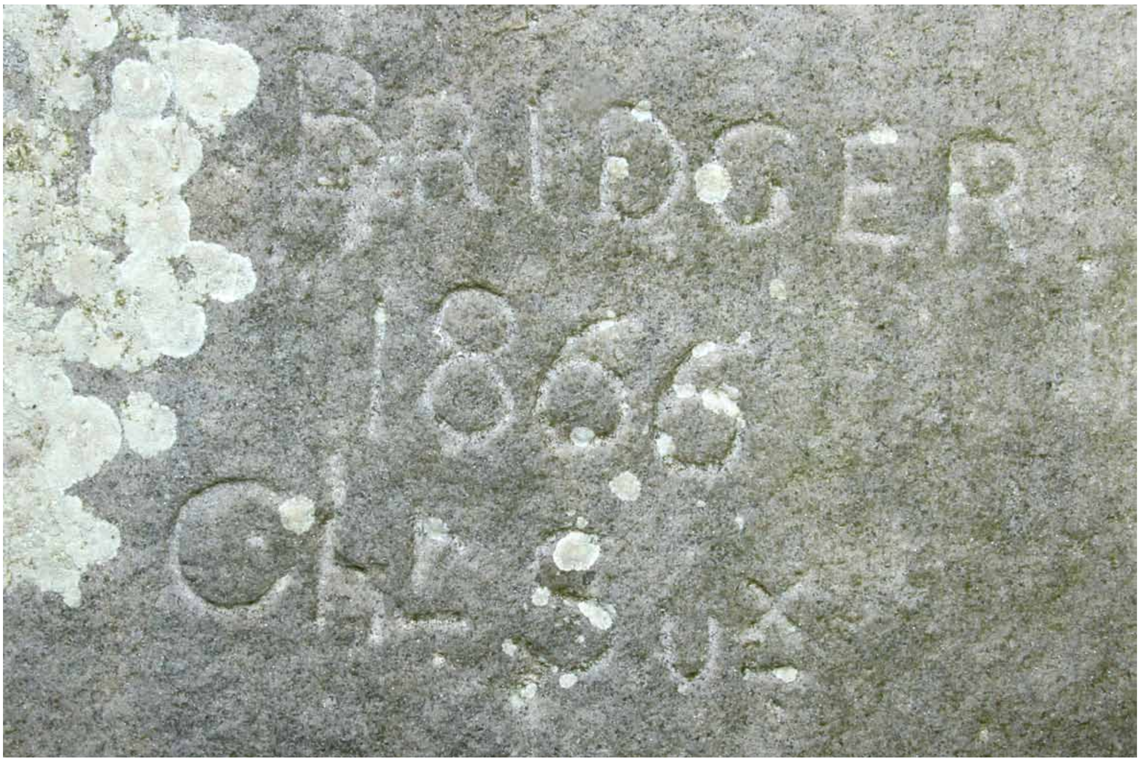

Figure 19. The latest dated graffiti at Stonehenge, recording a visit by H. Bridger of Chichester, Sussex in 1866 (Photograph Hugo Anderson-Whymark)

concentration of carvings, along with the regularity of the stone dressing of these stones, may indicate that they are more easily carved than the other sarsens.

Hammering and the taking of mementos

From the illustrations of Lucas De Heere (1574), Inigo Jones (1655), John Aubrey (1666), William Stukeley (1740) and John Wood (1747), we can establish that no complete stone has been removed from Stonehenge since the middle of the 18th century (Lawson and Walker 1995, 345). Many thousands of small chips have, however, been removed as mementos of visits to the monument. William Stukeley (1740) was the first to record this practice noting 'I was obliged with a Hammer to labour hard three Quarters of an Hour to get but one Ounce and a half' (1721-4, quoted from Chippendale 1985, 9). The practice of taking chips from stones may, however, have started much earlier, even within the lifetime of the monument if we consider the inclusion of chips of rhyolite in the Y and Z holes (Atkinson 1956, 21). Moreover, did the Romans take mementos in addition to digging holes and leaving offerings?

It is clear from extensive flaking to the edge of Lintel 158, which fell on the 3rd January 1797 and was re-erected in 1958, that a great deal of damage to the monument occurred in the 19th century. Indeed, a letter to the Times in 1871 complained that hammering was disturbing the peace at Stonehenge (Pitts 2001, 82). Thankfully, the removal of chips of stone as mementos has long since ceased, although the detachment of a small chip from the Heelstone in 2008 demonstrates that some vandals will still go to great efforts to obtain a piece of the monument.

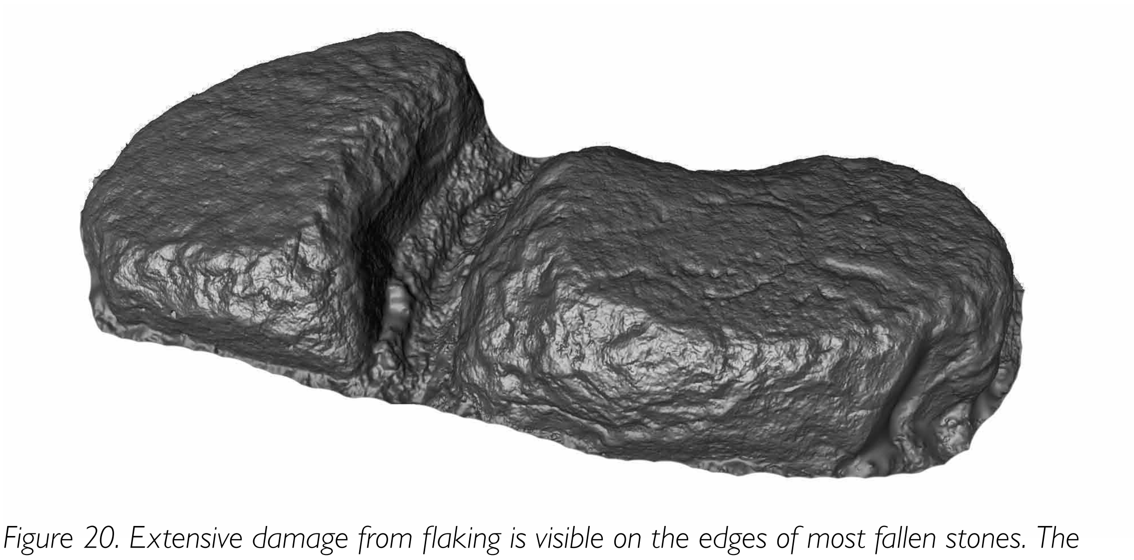

Figure 20. Extensive damage from flaking is visible on the edges of most fallen stones. The edges of Stones 9a and 9b have been very extensively damaged

In total, 55 areas of intentional damage from flaking were recorded on 34 stones (or 40 stones, if we count the individual fragments of broken stones separately). Fallen stones of the Sarsen Circle and Sarsen Horseshoe were the focus of particular attention, presumably as they provided a convenient seat while one hammered. Indeed, the only upright sarsen stones that exhibit any damage from flaking are Stone 56 (along the edge accessible from Stone 55, when the stone was leaning prior to 1901) and Stone 11 (again a leaning stone that exhibits flaking along one edge). The damage present on many of the fallen sarsen stones is dramatic. The edges of once regular stones have become rounded and, in extreme cases, very little of the original faces survive (*e.g.* Stone 8, Stone 9 and Stones 160a, b, and c; see Figure 20). To the untrained eye, these stones are now little more than amorphous lumps.

The bluestones have also suffered damage, but it was not just fallen stones that were subjected to hammering. The crisp edges of the stones in the Bluestone Horseshoe were particularly vulnerable and Stones 61, 62, 63, 69 and 72 all exhibit sub-conchoidal scars resulting from the removal of flakes. In all cases on stones of the Bluestone Horseshoe, the flake scars are in fresh, unweathered condition, while the dressed surfaces exhibit a weathered patina. This indicates that these flakes were detached long after the stones were dressed, and probably within the last few centuries (Figure 21).

It should also be noted that, despite the removal of many tons of stone in small chips, very few of these mementos now survive, indicating that most are likely to have been subsequently lost or discarded. This chipping will also have contributed to the Stonehenge layer.

Footfall, barbecues and other damage

In addition to the intentional damage caused by visitors to Stonehenge, various forms of incidental damage have been caused. Polish and wear from footfall is apparent on many of the fallen stones, but the fallen bluestones have fared worst than the sarsens. Stones 38, 39, 40 of the Bluestone Circle and Stones 67 and 72 of the Bluestone Horseshoe

Figure 21. Visitor flaking to the SW edge of Stone 62; Note the weathered stone surface and unweathered flake scar (Photograph Hugo Anderson-Whymark)

Figure 22. Polish from footfall on the exterior SW (now upper) surface of Stone 67 (Photograph Hugo Anderson-Whymark)

all exhibit considerable wear to their exposed surfaces and, in most cases, this damage appears fresh; these stones lie in parts of the monument where they are still frequently stepped upon to negotiate other fallen stones (Figure 22).

On at least one occasion, damage was caused by lighting a picnic fire against the stones. William Cunnington commented in 1867 that:

> 'On 17th July last a party of Goths lighted a fire against one of the stones on the south-east side of the outer circle, by which it was quite damaged and disfigured, and several fragments were broken off by the heat.' (Wiltshire Archaeological Magazine, Vol. 2, 348, quoted in Stone 1924, 85)

The location of this damage has not been identified. It is possible that this damage was masked by vegetation in the laser scan, as it would have been at the very base of a stone, but equally subsequent visitor damage may have removed all trace of this fire damage.

PART 4: DISCUSSION

The laser scan data and considerations for future high-resolution surveys

The analysis of the Stonehenge data set has led to the creation of a suite of techniques, all of which can be utilised on future digital projects. The result of our research demonstrates that a multi-methodological approach is most beneficial to the analysis of a multi-format (i.e. point cloud, mesh, and photogrammetric) data set. The process of working with multiple data sets has enhanced existing techniques, created a semi-automated workflow for the generation of virtual PTM files, and investigated the potential of utilising surface normal maps to enhance the overall project objectives. Although not originally part of this project brief, our research has created a comparative data set through experiments in photogrammetric recording of the stone surfaces. This is a prime area for future research into a survey technique which can cost effectively collect the data needed to create detailed meshes. Additionally, this project has given rise to a new method of analysis with numerous potential applications. Luminance Lensing uses a custom material shader for the visualisation potential of sub-millimetre meshes. This new technique is applicable to meshes created from both laser scan and photogrammetric data sets and can be used in conjunction with other visualisation techniques such as PTM and real-time scientific visualisation. Because Luminance Lensing is compatible with low cost photogrammetric data collection workflow solutions such as Agisoft PhotoScan, it is highly applicable to many heritage sites.

It is worth noting some of the issues and challenges we experienced with the Stonehenge data set can help improve data collection on future projects. Some of the meshes displayed 'artifactual' elements, possibly derived from the meshing process. Some clear cut features seemed 'blurred' in the mesh data despite the tight polygon density of the mesh. We attempted to re-mesh the original data to remove the unwanted elements, but our attempts resulted in similar meshing defects. This evidence seemed to suggest that the main cause of these issues was related to the original laser scan, rather that the meshing process. Examination of the point cloud data revealed multiple point clouds that were not perfectly aligned. We assigned each point cloud with a different colour in order to clearly associate points with their parent cloud and cross-sectioned the data; occasionally a misalignment of 2-3mm was present in cloud-to-cloud registration. Ordinarily this minor imperfection would have little or no effect on a survey, and indeed it is almost impossible to see other than when examining the data at a sub-centimetre level. However, it stands to reason that a 2mm shift will affect the 1mm and 0.5mm meshing of the data. As the algorithm unifies the data it will average out the misaligned clouds creating a high density mesh but with less surface detail, and therefore it is likely that smoothing and blurring issues are linked to the 2mm misalignment in the point cloud registration.

Arguably the biggest challenge conducting a survey at this level of detail is the control that links point cloud to point cloud. The sub-millimetre accuracy required when establishing point cloud controls is a challenge for even for the most diligent of surveyors. The Stonehenge project was particularly challenging in this area because of the scale of the sub-millimetre survey. This sort of sub-millimetre precision is normally associated with manufacture, and seldom seen in buildings or landscape survey. Alternative survey methodologies may be able to limit the effects of these issues and should be considered on future projects. In particular, avoiding oblique scans over large distances may help to remedy this issue.

Lastly, there are additional unidentified shapes and 'shadows' in the data sets which in future may prove to be of importance. We have had great success in revealing a number of new carvings, but there are still features which are very suggestive of prehistoric artwork and do not appear natural. These shapes may represent highly eroded carvings, but they were excluded from the feature list because we were unable to adequately define their limits and form. With further development of the techniques outlined in this project, it might be feasible to clarify the nature of the unidentified shapes noted in the data set.

Archaeological analysis

Analysis of the laser scan data has revealed significant new evidence that enhances our understanding of various aspects of Stonehenge, from the techniques employed in its construction, through the addition of prehistoric carvings in the Early Bronze Age, to collapse, breakage and the activities of tourists. The key aspects are discussed below.

Stones, stone-working and the architecture of Stonehenge

Stonehenge is a complex and enigmatic monument. The date, sequence and form of many of the key structural elements are unclear and subject to re-interpretation (Darvill *et al*. in press; Parker Pearson 2012). We can be certain that the monument began around 3000 cal BC with a circular bank and ditch, surrounding 56 Aubrey Holes that contained either stones or timbers. The second phase of the monument involved the erection of the Sarsen Horseshoe, Sarsen Circle and an enigmatic bluestone structure contained in the Q and R holes, which through the presence of bluestone Lintels 36 and 150 included at least two bluestone trilithons. This bluestone structure was dismantled at some point, possibly while it was still being constructed, and the stones were re-used to form a Bluestone Horseshoe or Oval, in the centre of the monument, and a Bluestone Circle located between the Sarsen Horseshoe and the Sarsen Circle.

Analysis of the stone-dressing techniques reveals that the bluestone trilithons, and other stones in this early structure, were dressed using the same techniques and in the same fashion as the trilithons of the Sarsen Horseshoe. This supports the possibility that these structures were contemporary. It is interesting to consider how the bluestones may have been erected in the Q and R holes. The bluestone uprights, with the notable exception of the finely dressed tongue-and-groove Stone 68, all exhibit fine dressing on a front face and both sides, but the back of the stones is left roughly dressed. This pattern of dressing is comparable to Trilithons 1, 2, 4 and 5, and it indicates that the broadest well dressed faces of these stones were probably orientated towards the centre of the monument. The shape of the seat on Lintel 36 and its pattern of frictional wear further contribute to the reconstruction of the earlier bluestone structure as these marks suggest that the broad faces of the uprights were parallel with the long axis of the lintel (i.e. this lintel and its uprights were constructed in the same arrangement as the Sarsen Trilithons). This indicates that the bluestone trilithon to which Lintel 36 belonged was probably erected facing the centre of the monument, rather than radially (i.e. straddling the Q and R holes) as any other orientation would result in the rough dressing being visible from the centre of the monument.

Lintel 36 is also only about 1.83m long, with a centre-to-centre gap between the mortises of *c*.0.85m, while Lintel 150, although much longer at *c*.2.44m, has similarly arranged mortise holes at *c*.1.04m centre to centre. It is difficult to envisage how these trilithons would have fitted into the Q and R Hole arrangement as very few holes are located close enough together to contain the uprights of these trilithons. Indeed, the only conceivable position for these trilithons with the Q and R Hole arrangement (as excavated) would be across the NE-SW axis of the monument. This position would also complement the dressing of the stones.

The distinct change in dressing techniques between the Bluestone Horseshoe/Sarsen Horseshoe and the Sarsen Circle is also of particular significance; it is difficult to conceive why these techniques should be different if these elements were contemporary, unless the two groups of stones were dressed by different people. It is, therefore, conceivable that the Sarsen Circle was added to the monument at some point after the Sarsen Horseshoe and early bluestone monument in the Q and R holes was erected.

The dressing of the Sarsen Circle is also of significance as it reveals that this is an architecturally complex structure, and not a regular circle of stones as is commonly envisaged. The architecture is orientated around NE-SW axis of the early earthworks and the Sarsen Horseshoe. The stones that straddle this axis have been finely worked to produce regular rectangular portals (Stones 30, 1 and 16; the corresponding edge of Stone 15 is missing), which correspond with that of the Great Trilithon. These breaks in the circle create sight lines towards the midsummer sunrise and the midwinter sunset, depending on which side of the Great Trilithon the viewer is stood; the latter can be viewed from the centre of the circle, while the former is seen from behind the Great Trilithon. Notably both sides of the Great Trilithon are well dressed, in contrast to the exterior faces of the other Sarsen Trilithons, further indicating the importance of both viewpoints. It should also be noted that the inner face of the Sarsen Circle is lined by flat faced stones that have been pick dressed, with the exception of a few more irregular stones that are masked from view if one stands within the Sarsen Horseshoe.

The architecture of the Sarsen Circle also reflects the important approach to the monument from the Stonehenge Avenue to the NE (*cf* Tilley *et al*. 2007). The stones deployed on the NE side of the monument are more regular and visually imposing than those to the SW. Regular trapezoidal stones, which provide an optical illusion of height, are placed towards the NE, while rectangular and irregular stones are placed towards the rear of the monument, between Stones 11 and 21. The lintels are also more substantial and more regularly worked towards the NE of the monument; the only complete lintel to the rear of the monument (Lintel 122) is very poorly worked.

The stone dressing also demonstrates the importance of the view from the NE and from the interior of the monument. All of the stone surfaces visible from within the monument have been pick dressed, as have all faces visible from the NE. This dressing removed the brown or grey crust that covers undressed sarsens to reveal a fine, bright, grey-white surface. The only stone faces that are not dressed are the external SW faces of Stones 14-16. Notably, the only other external faces present in this half of the monument are coarsely dressed (Stones 10 and 11) or irregular (Stone 21). This confirms the view that the sarsen circle was not supposed to be approached, or perhaps even seen, from this southwest direction (Tilley *et al*. 2007). Instead, the emphasis was on the approach from the NE, facing towards the midwinter solstice sunset.

Incomplete or imperfect and damaged: the non-completion theory re-considered

Ever since John Wood (1747) wondered why so many of the lintels were missing from Stonehenge, and how any would-be stone robber might have removed them without damaging the uprights, successive authors have questioned whether Stonehenge was ever finished. After accurately surveying the monument, William Flinders Petrie invigorated the debate, stating:

> 'The evidence for non-completion of the outer sarsens, is in the very much smaller Stone 11.... Again Nos. 21 and 23 are both defective in size compared with the rest; these show that 11 was no single freak, but was the result of not having better material. If the builders ran so short as to have to use such a stone as 11, is it not very probably that they had not enough to finish the circle?' (Petrie 1880, 16)

This issue is still hotly debated; Christopher Tilley *et al.* (2007) argue that the monument was not completed, while Anthony Johnson (2008, 146) argues for a finished monument. This debate was also considered by David Field and Trevor Pearson following their survey of Stonehenge (2010, 62-66). Analysis of the laser-scan data has revealed significant new evidence that informs, rather than solves, this debate. Key aspects of the non-completion theory are reviewed. These are:

- The presence and use of 'inadequate' stones (*e.g.* Stones 11 and 21).
- The absence of approximately one third of the Sarsen Circle on the SW side of the monument and the absence of the majority of the lintels.
- The absence of documentary evidence for the removal of stones or slighting of the monument.

The use of inadequate stones, particularly on the SW half of the monument, is central to the non-completion theory. The diminutive Stone 11 has been subject to the most debate: it is not only narrow, it is the only upright not of full height. This study has observed that Stone 11's top is broken off, confirming the views of Lukis (1882), Stone (1924) and Atkinson (1956). The stone may well, therefore, have stood to full height and, if its current width was maintained, the *c.*1m-wide stone top would have provided a more than adequate seat for the ends of two lintels (*cf* Johnson 2008). There is, however, no doubt that many of the stones in the SW part of the Sarsen Circle, particularly from Stone 11 to 21, are less substantial and regular than those on the NE side of the monument. We have argued above that the positioning of individual stones, based on their size, shape and pattern of dressing, is an important aspect of the architecture of the Sarsen Circle. The largest, most regular and finest dressed stones are positioned towards the NE of the circle, where they are viewed as one approaches the circle from the Avenue. The view from the centre of the monument is also significant but, due to the masking effect of the Sarsen Horseshoe, the most important faces are again those on the NE side of the monument. The absence of dressing on the exterior surfaces of stones on the SW of the Sarsen Circle indicates that the monument was not designed to be approached from this direction.

In the non-completion theory there are two common implicit assumptions:

- That the circle was of uniform construction, *e.g.* '*The planned norm would appear to have been Stone 29, 30 and 1 to 7*' (Ashbee 1998, 139)

- That the raw materials from which Stonehenge were constructed were not identified before construction started and the supply of materials was exhausted, *e.g.* '*An examination of the stones at Stonehenge would appear to shew that the builders were unable to obtain sufficient material of suitable quality and of large enough size to properly fulfil their requirements. They had to take what they could get rather than what they would have desired. This indicates a very limited supply.*' (Stone 1924, 73)

The argument for a 'planned norm' is certainly questionable and one may argue that this issue is compounded by the way in which we commonly view Stonehenge: through plans and artificially elevated bird's eye-view reconstructions. Both of these viewpoints encourage us to consider the Sarsen Circle as a regular structure, as from these perspectives we can see a perfect circle. Moreover, in the artificially elevated views it is possible to see the outer face of the circle in the foreground and the inner face at the back of the circle. On the ground – the viewpoint for this monument in the Neolithic – far less of the circle can be appreciated from a single viewpoint. When standing on the Stonehenge Avenue, one can see the exterior faces of the NE half of the monument; however, due to the curve of these, it is not possible to see the precise form of each stone. The visual illusion of regularity from this perspective may well have influenced the positioning of individual stones on this side of the monument. For example, Stone 3 has a very large flake scar on the exterior NE edge, but this irregularity is not visible from the Avenue: the break is in plain view but does not affect the outline of the stone. However, had this stone been erected in the NW quadrant, *e.g.* in the position of Stone 27, this irregularity would have been all too clear. Similarly, the large irregularities on the tops of Stones 27 and 28 are not particularly visible from the Avenue, as they directly face the observer. Yet had these stones been used on the SE or NW side of the monument, they would clearly have stood out. Similarly, the stones that can be seen most clearly from the centre of the monument are the most regular, well-dressed faces.

The argument for a 'shortage' of raw materials is particularly problematic. The assumption that a design was generated before stones were identified implies that the stones were little more than building blocks, comparable to material we might purchase from builders' merchants. The stones themselves are however likely to have been of some significance to the builders of Stonehenge who were prepared to go to considerable lengths to bring stones from as far away as west Wales and north Wiltshire. Rick Peterson's recent discovery of William Stukeley's 1723 drawing of shaped sarsen stones at Clatford near Avebury indicates that stones of sizes equivalent to those of the Sarsen Circle were available less than 20 miles away (Parker Pearson 2012, 297; Piggott 1948).

The absence of many stones from Stonehenge, combined with the absence of documentary evidence for their breakage or removal, forms another cornerstone of the non-completion debate. Analysis of the laser-scan data has revealed that significant portions of most fallen stones have been removed from Stonehenge. Indeed, the quantity of stone removed was very significant. The differential preservation of the NE and SW halves of the monument still requires explanation, particularly as the evidence for deliberate slighting is minimal and is confined to the attempted breakage and burial of the Slaughter Stone at some point prior to the 19th century (*cf* Ashbee 1998). It should, however, be noted that those sarsens that have pieces missing are the fallen ones, with the sole exception of Stone 11. This indicates that these fallen stones were easy prey for stone robbers. It is therefore worth questioning whether the pattern of fallen stones results from differences in construction between the NE and SW halves of the Sarsen Circle. It is certainly clear that the smaller stones have been used towards the rear of the circle and, in the case of Stone 13, this was set in a very shallow stone hole. During his visit in 2009, Malagasy archaeologist, Ramlisonina noticed that many of the fallen stones have tapered and narrow bases: when these stones were erect and *in situ*, their above-ground part would have given the appearance of symmetry with a rectangular shape whilst their less symmetrical and less stable bases would have been hidden below ground, sacrificing long-term stability and hence contributing to their collapse (Parker Pearson 2012, 293). Thus, if the less suitable monoliths were used in the SW, these may have been the ones with the least stable bases.

In conclusion, this study provides evidence that 27 of 30 uprights of the Sarsen Circle were certainly erected, and the presence of tenons on adjacent uprights may indicate that all were present along with at least 26 of the 30 lintels. There is certainly no convincing evidence that the circle remained incomplete, and in the light of the significant degree of demonstrable stone robbing, it is possible that a complete Sarsen Circle once existed. It is, however, clear that the Sarsen Circle was never a perfectly symmetrical circle of regular pillar and lintels. Its SW half was not as well constructed as the surviving NE half; the stones were smaller, less regularly shaped and their exterior surfaces were left coarsely dressed or entirely unworked.

Rock art and the meaning of Stonehenge in the Early Bronze Age

The Neolithic builders of Stonehenge went to extraordinary efforts to shape the stones and dress the faces of the monument, but they left no convincing carvings or motifs. Richard Atkinson's (1979, 209) claims for the presence of Neolithic Passage Grave art on Stone 3 cannot be substantiated (one wonders if the pattern he was referring to was formed by the two lines of axes on Stone 4), and many other reported carvings, such as quadrilaterals, snakes, 'torsos' and cup marks are no more than natural irregularities, areas of stone dressing, or the results of differential weathering.

The only convincing carvings on Stonehenge are of axe-heads and daggers. In total, 115 possible or certain axe-head carvings and three dagger carvings have been identified. These motifs occur in four key panels (the exterior E faces of Stones 3, 4, 5 and the

NW interior face of Stone 53), but four motifs are found elsewhere. The carving of one axe-head was found on the N face on Stone 5, two axe-heads formerly identified as a dagger were found on the SW face of Stone 53 and a dagger is present on the SW face of Stone 23. The axe-heads are readily identifiable as a form of flanged bronze axe with distinctively splayed edges that was in circulation around 1750-1500 cal BC; the dagger styles would also fit this date range (Needham 1996, Stage 4; Needham, Bronk Ramsey *et al.* 1998; Lawson 2007). Stonehenge was, therefore, almost a thousand years old before the first carvings were made on the stones.

The period of time between the erection of the stones and the carving of the axe-heads and dagger was also a period of considerable social change. Metal, Beaker pottery and individual burial practices were adopted from Europe, while the use of Grooved Ware and henge monuments ceased. At Stonehenge, there is evidence for activity in the Early Bronze Age, for example, from the 229 Beaker sherds, weighing 1019g, recovered during the twentieth century excavations (Cleal *et al.* 1995, 353). The Y and Z Holes may also have been cut in the Early Bronze Age (Cleal *et al.* 1995, 524), but we have little evidence of how the monument was used at that time. In this respect, the position of the panels of carvings on the exterior E faces of Stones 3-5 is of interest as these faces were of no particular significance in the Neolithic (when the emphasis was on views along the NE-SW axis from the Avenue, from the centre of the monument, and from behind the Great Trilithon). This implies that the meaning and use of Stonehenge had changed.

The axe-head carvings at Stonehenge can be paralleled at four other sites in Britain (see Prehistoric Carvings discussion above), but only one of these sites, the Badbury Barrow in Dorset, has axe-head and dagger carvings. These parallels, however, have not been identified on Neolithic stone monuments: they are carved into the sides and capstones of cists within barrows. The intimate association of these carvings with burials is potentially of great significance, and one may interpret these carvings as offerings to the dead, perhaps conveying something of the wealth and position of the bearer (Lawson 2007, 254). The panels of Early Bronze Age carvings at Stonehenge are the largest in Britain, and they account for 83% of known axe-head motifs and three out of six dagger carvings. Evidence for Early Bronze Age burial at Stonehenge is slight, with the notable exception of the Beaker-period burial in the ditch that pre-dated these carvings, although many of the scattered remains and two graves are undated (Cleal *et al.* 1995, Appendix 2). However, in the wider landscape Stonehenge had become the focus for one of the densest clusters of Early Bronze Age barrows in Britain, the centre of a burial complex. In this respect, Stonehenge's axe-head and dagger carvings are comparable to those on cist in barrows.

Conclusion

Conducting this project has added significantly to the understanding of the benefits and limitations of working with digital data to analyse monuments like Stonehenge. It has demonstrated that the data set provided by English Heritage contains a wealth of valuable digital information. ArcHeritage were able to visualise and interpret this data to enhance our understanding of Stonehenge and to make important new discoveries about the prehistoric techniques of working, constructing and finishing the stones. Through the identification of patterns of weathering, damage and erosion, we have been able to assess the effect of these processes on the wider context of the monument and its management. Lastly, significant numbers of previously unrecorded prehistoric carvings have been discovered on the monument, a remarkable national increase of double the previous number of these rare Bronze Age artworks.

Ever since Tom Goskar and colleagues from Wessex Archaeology/Archaeoptics first employed laser scanning on the surfaces of Stonehenge in 2003 (Goskar *et al*. 2003), it was clear that this technique held great potential. The results of the analysis of the laser scan data of the stones is, however, beyond all expectations as it has been a long held belief that the most of traces of surface dressing and many prehistoric carvings had been weathered beyond recognition. The patterns of stone-working not only reveal how the monument was constructed, but they provide additional evidence that can be used to understand the form of the dismantled bluestone monument and the chronology of other structural elements, such as the Sarsen Circle. The study also contributes to the debate over whether Stonehenge was completed. The discovery of numerous new prehistoric carvings also enhances our knowledge of the use of the monument in the Early Bronze Age.

The strength and success of this project lies in its sound research strategy. The project not only focused on using laser scan survey to simply record Stonehenge, but also to learn from this data and to gain new knowledge about the monument. By far one of the most encouraging and exciting aspects to this project is that even though Stonehenge has been subject to decades of extensive study, the application of cutting edge technology has brought about significant new discoveries. This stands as a testament to the benefits technological advancements can bring to heritage projects when incorporated into a sound research strategy. In contributing to a greater understanding of the monument of Stonehenge, this survey and analysis project has laid the foundations for the evolution of a working methodology in the capture and analysis of high-resolution survey data for heritage projects. The intelligent use of high definition survey data as a non-intrusive investigation tool has the potential for a wide ranging and exciting impact on the way archaeologists and heritage professionals perceive and utilise technology on future projects.

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APPENDIX 1: THE SURFACE AREA, VOLUME AND ESTIMATED WEIGHT OF STONES AT STONEHENGE

Table 1: Surface area, volume and estimated weights of the Sarsen stones. These calculations are for the above ground portions of stones only. Estimated above ground weight has been calculated assuming sarsen has a specific gravity of 2.4.

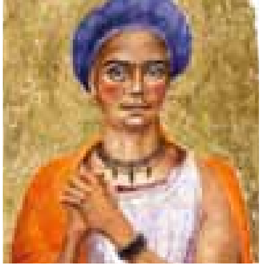
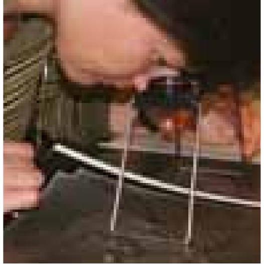
Stone No.	Surface Area (m²)	Volume (m³)	Estimated above ground weight (tons)
1	22.32	5.45	13.08
2	27.67	8.03	19.27
3	24.5	5.55	13.32
4	24.07	6.66	15.98
5	22.54	5.64	13.53
6	23.29	5.54	13.29
7	20.89	5.97	14.32
8*	4.5	0.65	1.56
9a/b*	1.17	0.25	0.29
10	24.31	7.07	16.96
11†	9.38	2.03	4.87
12‡	13.66	6.32	15.16
14‡	15.41	2.91	6.98
15*	3.84	1.31	3.14
16	25.63	9.8	23.52
19*	6.47	1.65	3.96
21	17.6	4.61	11.06
22	21.77	5.47	13.128
23	20.09	4.92	11.8
25*	10.27	2.95	7.08
26*	3.29	0.4	0.96
27	23.88	5.21	12.48
28	27.04	9.08	21.792
29	23.19	6.95	16.68
30	24.35	7.75	18.6
51	34.11	9.86	23.66
52	34.29	11.54	27.69
53	29.48	7.56	18.14
54	36.6	12.22	29.32
55a/b*	37.91	6.6	15.84
56	38.48	9.61	23.06
57	36.42	11.64	27.93
58	37.87	10.02	24.04
59a/b/c*	19.64	9.1	21.84
60	36.18	9.01	21.62
91	5.07	1.16	2.78
93	3.09	0.56	1.34
95‡	14.86	1.75	4.2
96	32.08	12.47	29.92
101	13.04	1.88	4.51
102	9.71	2.7	6.48
105	9.2	1.59	3.81
107	11.35	2.1	5.04
120*	2.7	0.49	1.17
122	13.6	2.7	6.48
127*	3.97	0.6	1.44
130	13	2.6	6.24
152	20.06	4.89	11.73
154	23.57	7.29	17.49
156	18.91	3.7	8.88
158	24.2	6.9	16.56
160*	9.4	2.09	5.01

* = fallen and fragmentary. † = standing and fragmentary. ‡ = fallen but complete. Note many fallen stones are partly buried.

Table 2: Surface area, volume and estimated weights of the Bluestones stones. These calculations are for the above ground portions of stones only. Estimated above ground weight assumes a specific gravity of 3 for dolerite and 2.4 for Rhyolite/Rhyolitic Tuff.

Stone No.	Surface Area (m^2)	Volume (m^3)	Estimated above ground weight (tons)
31	4.968	0.68	2.04
32‡	2.04	0.38	1.14
33	2.03	0.17	0.51
34	1.54	0.11	0.33
35a‡	0.06	0.0007	0.002
35b‡	0.14	0.003	0.01
36‡	0.58	0.09	0.27
37	2.92	0.27	0.81
39‡	1.32	0.16	0.48
41‡	1.3	0.24	0.72
42‡	1.27	0.1	0.30
45‡	1.28	0.14	0.42
46†	1.97	0.14	0.34
47	3.4	0.42	1.26
48‡†	1.33	0.066	0.16
49	4.21	0.37	1.11
61	2.86	0.32	0.96
62	3.44	0.41	1.23
63	3.4	0.4	1.20
67‡	3.14	0.53	1.59
68	5.06	0.71	2.13
69	5.1	0.72	2.16
70	3.7	0.41	1.23
72*	0.69	0.51	1.53

* = fallen and fragmentary. ‡ = fallen but complete. Note many fallen stones are partly buried. † = Rhyolite/Rhyolitic Tuff.



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ENGLISH HERITAGE

ISSN 2046-9799 (Print)
ISSN 2046-9802 (Online)